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The Geologic Implications of the Factors that Affected Relative Sea-level Positions in South Carolina During the Pleistocene and the Associated Preserved High-stand Deposits

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DEDICATION

This project is dedicated to my family and friends who supported this endeavor and to Emily Ann Louder, my daughter, who at this time has no understanding of why her father is still in school, but is so excited that I am. May she continue to find excitement in, and support for, what interests her in her future.

And to all of who ask the questions, "*What, Where, How,* and *Why*", all of which are easy compared to the follow up question of "*Why should anyone else care?*", I dedicate this to you in memory of your time, effort, record of work, and the not-recorded trials and tribulations you faced on your journey.

EVER FORWARD

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I specifically thank Terry Woods, a professor at East Carolina University during my undergraduate program (1988-1993), for giving me THE chance. Without her I would never have become a geologist.

ABSTRACT

This work utilizes the current understanding of South Carolina geology to provide a stratigraphic review of the late-Pliocene and Pleistocene marine deposits. Almost two centuries of recorded geological study includes geomorphic and stratigraphic units that were described, proposed, revised, abandoned, and revived. Along with the history of the age assignments, changes in geological time scales, and the changes in the understanding of geological concepts, this review is necessary because two concurrent and conflicting stratigraphies exist for late-Pliocene and Pleistocene marine sediments that record multiple sea-level transgressions that were more often destructive than constructive. The result, when tested against existing geological data covering >22,000 km^2, is a set of interpretations providing a revised and unified geomorphic and stratigraphic nomenclature. Eleven stratigraphic units occur only in the subsurface. Ten Plio-Pleistocene highstand deposits are preserved at the surface: one Pliocene, eight Pleistocene, and the current transgression. When the Pleistocene highstand elevations and geochronology were compared to sea-level reconstructions, based on predicted elevations from marine isotope studies, only two highstands matched. Other observed highstand elevations are higher than predicted by reconstructions. The factors affecting relative sea-level changes were studied to rectify the gap between the observed and predicted elevations. When applied, the factors partially reduce the gap; however, the results suggest that the processes affecting post-depositional changes in shoreline elevations are complex and not completely understood.

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CHAPTER 1

Introduction

This work reviews and compiles the existing literature, proposes a refined stratigraphy based on facies associations and geochronology, presents the conceptual stratigraphic model that stratigraphy is based on, compares the stratigraphic results to studies from various locations around the world, compares the factors that affect relative sea-level change, and attempts to rectify the differences between observed/mapped elevations and the predicted elevations.

This geological study started as a review and synopsis of Pleistocene surficial marine stratigraphic units in the Lower Coastal Plain of South Carolina. The focus was on the deposits seaward from the Surry Scarp (+29 to 27.4 m elevation), which formed at a time when the Surry Scarp marked the inland limit of those sediments in South Carolina (Johnson, 1907; Flint, 1940). However, downward revision in the age of the base of the Pleistocene from ~1.8 Ma (Berggren and others, 1995) to 2.588 Ma (Gradstein and others, 2004; Gibbard et al., 2010) in effect physically moved that temporal boundary inland to the Parler Scarp (+42.67 m) (Doar and Kendall, 2014) and forced a broader study: the no-longer Pliocene deposits were then considered. Also, this expansion (800 ka) in meaning of the word “Pleistocene”, and resulting contraction in meaning of the word “Pliocene” (Gibbard et al., 2010), have resulted in a significantly different use of

“Pliocene” and “Pleistocene” in the Atlantic Coastal Plain compared to previous decades.

The study area lies on the eastern coast of North America, the western side of the North Atlantic Ocean, on the Atlantic Coastal Plain. Following the opening of the Atlantic Ocean, about 180 Ma, the Atlantic coast of North America became a trailing edge margin. Presently the Atlantic Coastal Plain of South Carolina is composed of a southeastward-dipping wedge of Cretaceous to Modern calcareous and siliciclastic sediment (Poag, 1985). As described in the later chapters, the Pliocene to Modern marine sediments are composed of siliciclastic sand and mud with some shell material. Due to the similar lithologic compositions between deposits of differing ages, the units are differentiated by unconformities, facies staking patterns, and geochronology.

The geologic implications of the factors that affected relative sea-level positions in South Carolina during the Pleistocene, and the associated preserved high-stand deposits, are important for understanding the geological history of the southeast coast of North America and can provide insights into possible revisions of the factors that affect relative sea-level positions. Correlating our work to other locations along the southeast United States coast provides a regional-scale perspective of the land-based records and it allows the analysis and comparison of the observed records with the predicted records. South Carolina’s Pleistocene marine coastal plain deposits are well developed and problematic. Lithostratigraphic-based mapping shows relative sea-level highstand elevations for the last 2 Ma of South Carolina ranging from 42.6 to 3 m above present sea level. However, sea-level reconstructions based on proxy data, such as marine isotope studies, do not predict sea levels from the same time period as having been higher than 10 m above present. Few observed sea-level highstand elevations agree with highstand elevations predicted by sea-level reconstructions based on proxy data. To attempt to reconcile the differences between the observed and predicted elevations, some factors that affect post-depositional elevation changes were calculated and applied to the current South Carolina highstand elevations. The possible factors calculated and applied were tectonics, glacio- and hydro-isostatic adjustment, sediment unloading and loading, and dynamic topography. Analysis of the complex processes acting on South Carolina's shorelines shows that the relative sea-level data, even after adjustments from the analysis, do not entirely fit predicted sea-level histories derived from studies far afield. Fewer highstands are preserved than predicted by Marine Isotope Stage (MIS) highstands for the same time interval and most are at differing elevations. This lack-of-fit between the observed and predicted global sea-level highstands indicates the complexity of determining past sea-level elevations. These analyses and comparisons, and partial resolution of the differences, highlight that not all processes post-depositionally affecting sea-level elevations are fully quantified, both for observed and predicted paleo sea-levels. Also, critical reviews of the quality of evidence, past interpretations, and assumptions upon which the interpretations are based, are necessary to move the science forward.

This review should be a cautionary tale for workers to remember that the issues related to any paleo sea-level reconstruction are complex. The Pleistocene highstands demonstrate that reconstructions of past sea-level require meticulous evaluation.

CHAPTER 2

Upper Cenozoic (post-Miocene) Marine Stratigraphy of the South Carolina Middle and Lower Coastal Plain[1]

[1]Doar, W. R., III and R. H. Willoughby. Submitted to South Carolina Geology, 11/6/2014.

ABSTRACT

This paper provides a stratigraphic review of the Pliocene and Pleistocene stratigraphy of the coastal regions of South Carolina. It utilizes the current understanding of the geology to provide a unified stratigraphy for the upper Cenozoic (post-Miocene) marine sedimentary deposits of South Carolina with updated age assignments. It reviews almost two centuries of recorded geological study in South Carolina, listing the many different stratigraphic units that have been described, proposed, revised, abandoned, and revived. In particular it traces the history of the changes in age assignments, changes in geologic time scales, and changes in the understanding of geological concepts. Importantly it records the occasional works that compile the history of nomenclature and state the current understanding of the geology.

The many physiographic features on the coastal plain of South Carolina noted by early workers are described. The relatively broad, flat landforms were called "terraces" and the narrow, steeper landforms were called "escarpments" (scarps). Investigations of surface exposures, excavations, and borehole samples have determined that often there is an association between the physiographic features and their underlying geology. As the state of geological understanding changed, new nomenclatures were proposed. One example is the existence of two competing and conflicting stratigraphies for the late-Pliocene and Pleistocene marine sediments. Both stratigraphies do agree that the Pliocene and Pleistocene sediments are a record of multiple sea-level transgressions and regressions. Authors have interpreted that the transgressions were often more destructive than constructive and may have partially or completely removed previously existing deposits. The result is that stratigraphies and interpretations compiled in the adjacent

states may not apply to South Carolina but are reviewed for possible correlation or inclusion. The history of the physiographic features, terraces and scarps, and the subsurface and surficial geologic deposits applied to South Carolina has been tested against the existing geologic data and revised interpretations are produced. This has resulted in recognizing ten terraces and their associated underlying deposits, identified as alloformations, which compose Middle and Lower Coastal Plain in South Carolina. Additionally, eleven stratigraphic units occur only in the subsurface.

INTRODUCTION

General Remarks

This study started as a review and synopsis of Pleistocene surficial stratigraphic units in the Lower Coastal Plain of South Carolina (seaward from the Surry Scarp) at a time when the Surry Scarp was considered to mark the inland limit of Pleistocene sediments in South Carolina (Johnson, 1907; Flint, 1940). Downward revision in the age of the base of the Pleistocene from ~1.8 Ma (Berggren and others, 1995) to 2.588 Ma (Gradstein and others, 2004; Gibbard et al., 2010) in effect physically moved that temporal boundary in South Carolina inland to the Parler Scarp (Doar and Kendall, 2014). Also, this 800 ka expansion in meaning of the word “Pleistocene”, and resulting contraction in meaning of the word “Pliocene” (Gibbard et al., 2010), have resulted in a significantly different use of “Pliocene” and “Pleistocene” in the Atlantic Coastal Plain compared to earlier decades. As an example, this change reduced the number of Pliocene surface stratigraphic units in the Middle Coastal Plain of SC. For that reason, the term “upper Cenozoic” is used in the title of this work to refer to Pliocene-to-Holocene

(Modern) deposits. An earlier work (Oaks and DuBar, 1974) used the term "post-Miocene" to avoid the same uncertainty of meaning in an earlier decade.

This study evolved into an evaluation of the published Pliocene and Pleistocene geomorphology and stratigraphy. As a result of that evaluation we are proposing abandoning the use of some terms and the revision of others for SC. The terms we propose to abandon appear in *italics* in the text.

Geological Setting

The Atlantic Coastal Plain (Murray, 1961) in South Carolina is situated on the southeastern coast of North America. Its underlying crust is composed of meta-volcanic, meta-sedimentary, and igneous rocks accreted to North America with the closing of the Iapetus Ocean and collision of Laurentia and Gondwanaland to form Pangea. The North American continent has been diverging from Europe and West Africa since early Mesozoic time (Manspeizer et al., 1978) when Mesozoic rifting (Horton and Zullo, 1991) led to the opening of the present Atlantic Ocean. As what is now North America pulled apart from what is now Africa, a saw-tooth pattern of promontories and embayments resulted along the east coast of North America. In South Carolina the coastal plain overlies the southern part of the Carolina Promontory and northern part of the Georgia Embayment (Thomas, 2006; Fig. 9). Half-graben structures that developed during the Mesozoic extension formed basins that filled with terrigenous and lacustrine sediments. As the Atlantic Ocean opened, east coast of North America became a passive margin and began building a coastal plain. By the Pliocene erosional unloading, sediment loading, and glacial- and hydro-isostatic processes became the major tectonic forces along the southeastern coast (NC, SC, and Ga). South of the Laurentide ice sheets, no glacial processes (Stiff and Hansel, 2004) and no collision tectonics or active volcanism occurred. Marine, coastal, and fluvial sedimentary processes dominated the coast. The Atlantic Coastal Plain (Murray, 1961) consists of unlithified to lithified sedimentary deposits of Cretaceous to Holocene age that form a southeastward-dipping wedge of calcareous and siliciclastic sediment deposited on a trailing edge margin (Poag, 1985). In general, South Carolina's coastal plain is divided into 3 physiographic provinces- the Upper, Middle, and Lower Coastal Plains (Figure 2.1) (Colquhoun, 1965; Colquhoun et al., 1991). The geometry of the coastal plain deposits is explained well by Soller and Mills (1991), "These sequences of deposits from successive transgressive-regressive cycles are preserved along the Coastal Plain, with progressively younger sequences lying nearer the modern coast and topographically lower than older sequences…Erosional, presumably wave-cut scarps developed in some places at the position of maximum transgression, thereby marking the landward extent of each cycle's deposits". Our research and studies have confirmed these statements and will be discussed further in this paper.

Basic Terms

Terms used herein to characterize stratigraphic units are: scarp, scarp toe, terrace, formation, unconformity, notch, alloformation, and base level.

Scarp

A scarp is "a relatively steep sloping surface that generally faces in one direction and separates level or gently sloping surfaces" (Neuendorf et al., 2005, p. 577). In the context of this paper scarps are erosional.

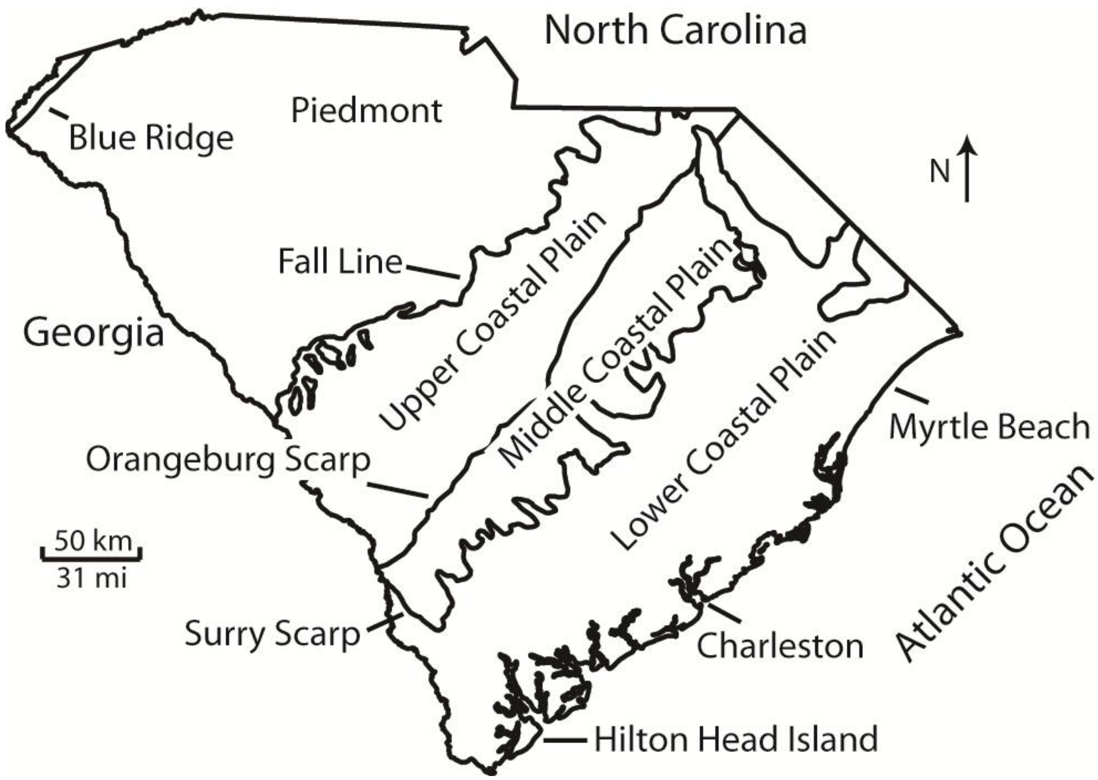


Figure 2.1. The Physiographic Provinces of South Carolina.

Toe of a scarp

The "toe" of a scarp is the point (elevation) where the surface of younger sediments touches, abuts, or overlies, an older, higher elevation, sediment surface; or, the surface expression of the unconformity that separates two deposits of differing ages; usually near the foot of a scarp slope. The foot of a slope is "the bottom of a slope, grade, or declivity" (Neuendorf and others, 2005, p. 249). The scarp toe is the surface expression of the unconformity between deposits and is a line in map view or a point in a cross section. The original toe position may not be preserved throughout the extent of a scarp due to later erosion or to the presence of younger deposits such as alluvium, eolian sand, or Carolina bay deposits. The foot of a slope is synonymous to toe in this usage.

Within our study area the toes of each Pleistocene marine scarp occur at similar elevations throughout their extent, indicating the land surface has undergone little differential (as opposed to absolute) warping or tilting along their length (Doar and Kendall, 2014). However, variation in elevation of the toe of the Orangeburg Scarp (a Pliocene marine scarp) throughout its extent does attest to warping or differential tilting of the land surface since its formation (Winker and Howard, 1977; Dowsett and Cronin, 1990).

Terrace

A terrace is defined as "a narrow, gently sloping, coastal platform veneered by sedimentary deposits and bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope" (Neuendorf et al., 2005, p. 663). Our definition of a marine terrace is- a narrow or broad, gently sloping surface underlain by sedimentary deposits, at least some of which are marine, and bounded along its landward margin by an ascending steeper slope (scarp) and along its seaward margin by a descending steeper slope (scarp) (modified after Neuendorf and others, 2005).

A marine terrace in the Atlantic Coastal Plain may directly face (on its seaward margin) the ancient position of the Atlantic Ocean, or it may face (seaward) into the throat of an ancient estuary or marine sound where its underlying sedimentary deposits are in part estuarine in character. Each Pliocene or Pleistocene marine terrace in the Atlantic Coastal Plain in SC faces, on its landward margin, older marine sediments.

A fluvial terrace is a usually narrow, gently sloping surface in the remnant valley of a present or ancient river or river system, underlain by sedimentary deposits at least some of which are fluvial in character, and bounded along its landward margin by an ascending steeper slope and along its outer margin toward the former thalweg by a descending steeper slope. A marine terrace may grade laterally into a fluvial terrace. Conversely, a given fluvial terrace in the Atlantic Coastal Plain may be related to a particular marine terrace or may be unrelated to any marine terrace.

Formation

A Formation is defined by the North America Commission on Stratigraphic Nomenclature (NACSN, 2005) as “a body of rock identified by lithic characteristics and stratigraphic position; it is prevailingly but not necessarily tabular, and is mappable at the Earth’s surface or traceable in the subsurface”. The formations of SC’s Coastal Plain are commonly tabular, mappable bodies of sediment that are identified by lithic characteristics, unconformable surfaces, and stratigraphic position. It is interesting that the definition quote “of rock” and yet, recognized formations composed of non-lithified sediments are accepted in the NACSN. We feel that there is an understood, but not defined, acceptance of “sediments” in place of “rock”. Pliocene and Pleistocene formations in the subsurface and at the surface in South Carolina’s Middle and Lower Coastal Plain’s meet these criteria.

Unconformity

The sequence stratigraphic concept of an unconformity is used. An unconformity is “a surface separating younger from older strata along which there is evidence of subaerial-erosion truncation and, in some areas, correlative submarine erosion, a basinward shift in facies, onlap, truncation, or abnormal subaerial exposure, with a significant hiatus indicated” (Neuendorf et al., 2005, p. 695). An unconformity is the irregular erosional surface that occurs at the base of a formation (or other stratigraphic unit) that underlies a marine or fluvial terrace. Names have seldom been applied to unconformities.

Notch

A notch is an unoccupied marine or fluvial unconformity: a bare, exposed, narrow, gently sloping, marine or fluvial unconformity (a surface) that is bounded along its inland margin by a steeper ascending slope and along its seaward, lakeward or riverward margin by a descending steeper slope. The steeper, ascending, inland slope of a notch encompasses the paleoshoreline. The steeper, seaward, lakeward or riverward slope of a notch is a scarp that descends either to a younger notch or to a terrace. The writers know of only one notch on the Atlantic Coastal Plain. The Silver Bluff erosional feature at Silver Bluff, Miami, Dade County, Fl. (Puri and Vernon, 1964) is a marine notch related to a landward paleoshoreline at approximately +2.1 to 1.2 m (7 to 4 ft) above present sea level (Cooke, 1945).

Alloformation

An allostratigraphic unit (alloformation) is a mappable body of rock that is defined and identified on the basis of its bounding discontinuities (North America Commission on Stratigraphic Nomenclature, 2005). For SC's formations at the surface, geomorphic characters (terraces, toes, scarps, elevations of occurrence) are valid reflections or markers of stratigraphic position; and fittingly these formations have been referred to informally as "terrace-formations" (Shattuck, 1901 a & b; Colquhoun, 1974) and morphostratigraphic units (Oaks and DuBar, 1974).

The sediments of a marine incursion or highstand that were abandoned at the surface by a subsequent marine relative lowstand constitute a separately recognized formal or informal stratigraphic unit (to include a formation), and the subaerially exposed surface of those sediments (or its erosional successor) constitutes a terrace.

Base level

The theoretical limit or lowest level toward which erosion of the Earth's surface constantly progresses but seldom, if ever, reaches…the general or ultimate base level for the land surface is sea level, but temporary base levels may exist locally (Neuendorf et al., 2005, p. 56). The base level for the east coast of North America is the Atlantic Ocean. The systems tracts for SC, therefore, are related to the changes in sea level for the Atlantic Ocean.

Evolution of Stratigraphic Concepts

For more than a century, workers have published descriptions of the geomorphic (physiographic) and geologic features and stratigraphic units along the central and southern North America, and a partial list is compiled in Table 2.1. Based on the work of

Table 2.1 List of Major Works that Influenced the Stratigraphy of South Carolina. These publications have influenced the lithostratigraphic concepts and stratigraphy of the Pleistocene section of South Carolina. They are listed chronologically with a brief summary of each publication's major point.

Publication	**Subject**
Tuomey, 1848	Geology of South Carolina
Dall and Harris, 1892	Review of stratigraphy
Shattuck, 1901 a & b	Established marine scarp and terrace concept and Wicomico and Talbot Formations in Maryland
Stephenson- In Clark et al., 1912	Pleistocene marine stratigraphy of NC; established many formations
Cooke, 1936	Map of SC coastal plain paleo-shorelines
Flint, 1940	Compiled stratigraphy
Richards, 1950	Updated NC stratigraphy
Malde, 1959	Proposed Ladson Formation
Colquhoun, 1965, 1974; Colquhoun et al., 1991	Expanded and refined Cooke, 1936 shorelines and formations
DuBar et al., 1974	Mapped NE corner of SC coastal plain
Healy, 1975	Mapped terraces in Florida
Newton et al., 1978	Age of the Waccamaw Formation
Wehmiller and Belknap, 1982	Geochronology
McCartan et al., 1984	Geological map and ages of SC Middle and Lower Coastal Plain deposits
Weems and Lemon, 1984 a & b; 1985; 1989; 1993	Geological Maps of parts of Charleston County, SC
Weems, Lemon, and Cron, 1985	Age dates and map of Charleston, SC area
Weems, Lemon, and McCartan, 1985	Geological Map of Charleston, SC area
Weems et al., 1987 a, b	Geological Maps of parts of Charleston County, SC

Johnson and Berquist, 1989	Revised Virginia coastal plain stratigraphy
Weems, Lemon, and Nelson, 1997	Geological Map of part of Charleston County, SC
Harris, 2000	Geological Map and age dates of Edisto Island and Adams Run, SC area
Weems and Lewis, 1997; 2002	Geological Maps of parts of Charleston County, SC
Doar, various years	52 Geological Maps of the Pleistocene section from Rockville, SC to Savannah, Ga; Santee, SC to Georgetown, SC; Allendale, SC to Savannah, Ga
Wehmiller et al., 2004	Geochronology
Doar and Willoughby, 2006	Refining the Pleistocene of SC
Parham et al., 2007	Geological map and age dates of NC
Mallinson et al., 2008	Geological map and age dates of NC
Doar and Kendall, 2008	Comparing the Pleistocene sea-levels of SC to other studies around the world
Graybill et al., 2009	Age of the Waccamaw Formation
Wehmiller et al., 2010	Geochronology and maps of NC
Weems, Lewis, and Crider, 2011	Elizabethtown, NC map, age and distribution of the Waccamaw Formation
Weems et al., 2011	Elizabethtown, NC open-file geological logs, extent of the Waccamaw Formation beneath the Marietta unit
Doar and Kendall, 2014	Pleistocene stratigraphy compared to Marine Isotope Stage-based sea-level reconstructions

Gilbert (1890; 1891) who associated the benches around Salt Lake City, Utah with former water levels of ancient Lake Bonneville, Shattuck (1901a, 1901b) proposed that the marine terraces along the coast of Maryland are the surface expressions of formations resulting from individual water-level (base level) change events. He named the Wicomico and *Talbot* formations on this basis. He did not name them formations in the sense of that word as defined later by the North American Stratigraphic Code (NACSN, 2005). Instead he looked for the erosional unconformity bounding the deposits in his boreholes and considered all sediments above that unconformity as part of his formation. Therefore, each formation may contain several lithic facies in common with other formations but which were parts of different events.

Cooke (1936) expanded Shattuck's concept when he produced a set of prior shoreline maps for the Middle and Lower Coastal Plain of SC based on the geomorphology of scarps and terraces (Figure 2.2). His maps are based on the geomorphology of the terraces, separated by escarpments (scarps), and supported by surface exposures and well data.

In the 1960's the North American stratigraphic code was well established and this made the existing definitions of these formations was problematic because the internal lithologies and geometries of established formations in SC no longer met the requirements of the code. The terrace names and formation names were often synonymous since the terrace partially defined the formation. Workers used the terms "morphostratigraphic units" (Frye and Williams, 1962) and "terrace formations" (Doering, 1960) to bridge the gap.

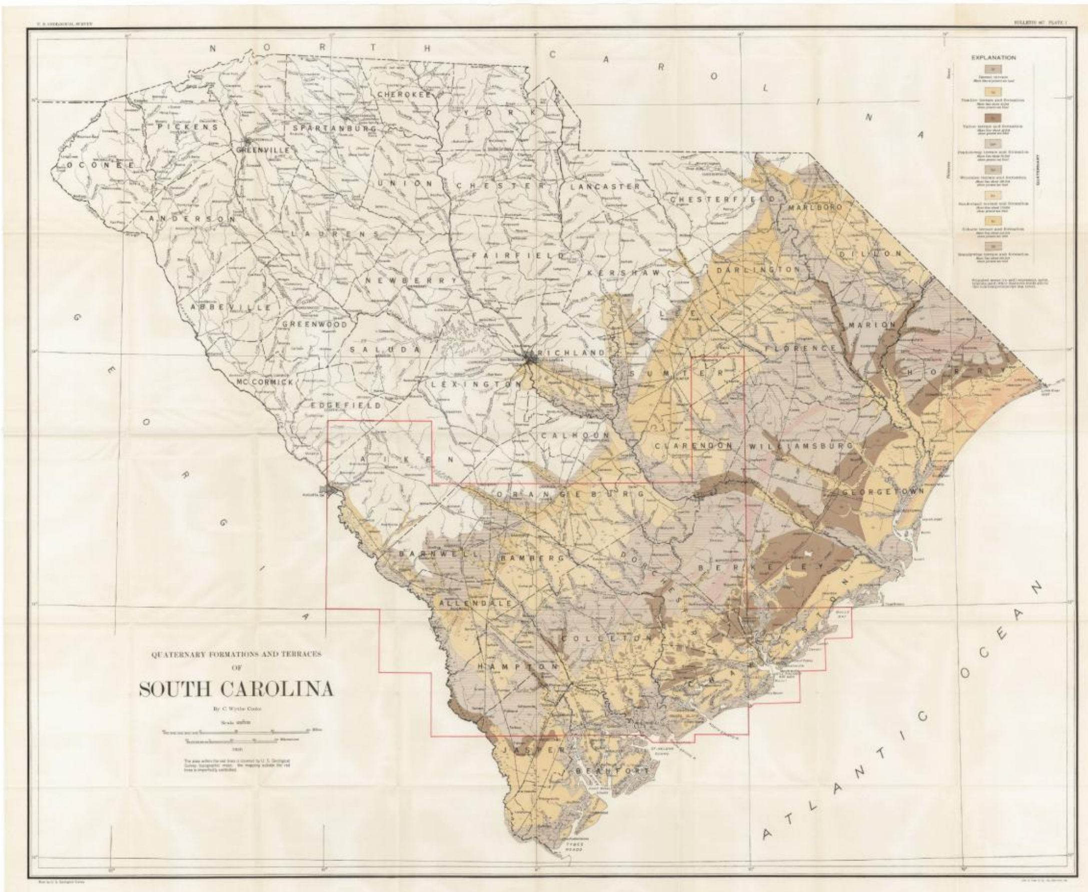


Figure 2.2. Coastal Plain Map by Cooke (1936). This is the first coastal plain map of South Carolina.

Frye and Williams (1962) developed the concept of a morphostratigraphic unit to use in the midwest because strict stratigraphic nomenclature and concepts would not allow recognition of units important in the Pleistocene history of that area. A morphostratigraphic unit is recognized and mapped largely on its surface form, not on the distinctiveness of the underlying material. As such, a morphostratigraphic unit has a geomorphic bias that was not allowed in standard stratigraphy. However, sedimentary bodies are the basis for definition of a morphostratigraphic unit and although erosion surfaces are not excluded they are not a primary consideration in the definition (Daniels, Gamble, and Wheeler, 1978). Alloformation (NACSN, 2005) now fills this gap and replaces morphostratigraphic unit and terrace-formation as standardized nomenclature.

Colquhoun (1965) followed Cooke's concepts. He was able to utilize a newer generation of more accurate topographic maps when he mapped the geomorphology of the South Carolina coastal plain and, with the addition of subsurface information from boreholes, was able to produce a more accurate map and cross section in the Summerville area (Figure 2.3). He later revised his assignments (Colquhoun, 1969 a, 1974; Colquhoun et al., 1991).

Contemporaneous with Colquhoun, J. R. DuBar was mapping in Horry County, SC and Columbus and Brunswick counties, NC. His work included deposits from the same time interval as Colquhoun's (Pliocene to Recent). As revealed in his borehole logs on file at the South Carolina Geological Survey, DuBar began by following Cooke's stratigraphic concepts and formation assignments. Nearing the end of this work, DuBar (1971) and DuBar et al. (1974) abandoned Cooke's concepts and established a new stratigraphy, not based on terraces, with fewer stratigraphic divisions (Figure 2.4).

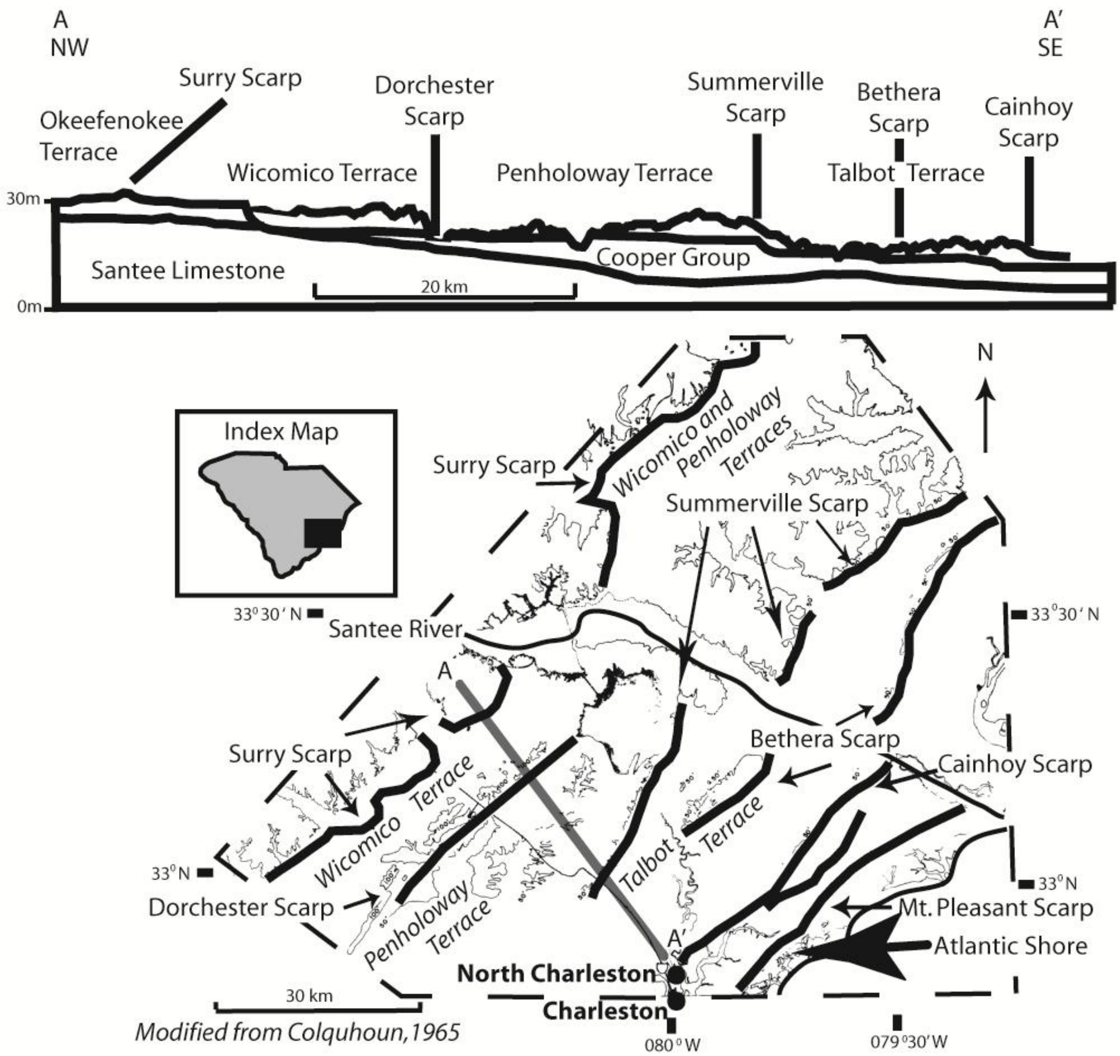


Figure 2.3. Generalized Geology Map and Cross Section of the Charleston and Summerville area, South Carolina.

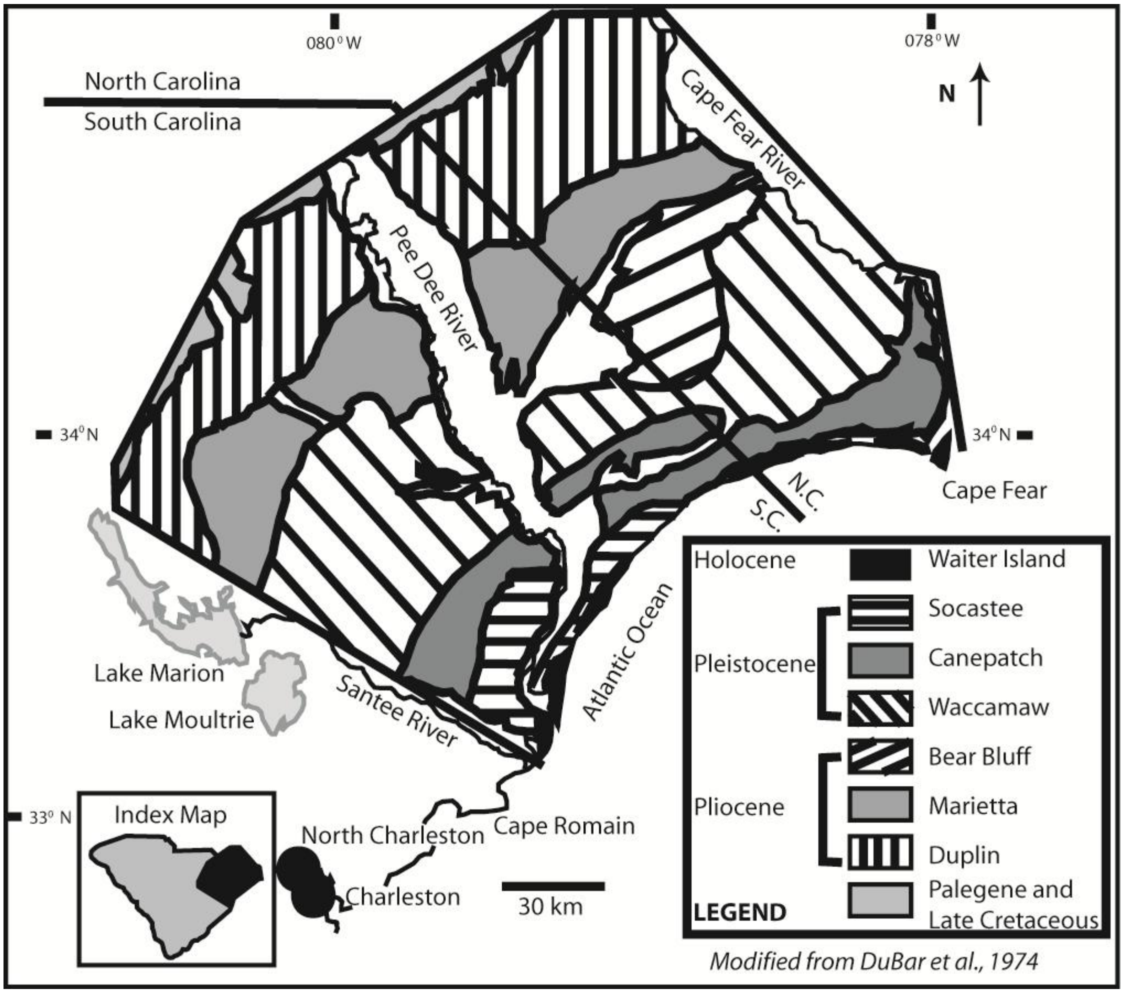


Figure 2.4. Generalized Geology Map of Northeastern South Carolina.

DuBar's work left confusion as to the overall nature and arrangement of the Pleistocene marine deposits for South Carolina and subsequent workers have chosen either the stratigraphy from Cooke and Colquhoun or from DuBar and others.

Stratigraphic and Temporal Assignments

Several names assigned to the Pliocene and Pleistocene geomorphic features and stratigraphic units in southeastern North America predate the now-standard nomenclatural system tied to an American or North American stratigraphic code (Ashley, 1933; North American Commission on Stratigraphic Nomenclature, 2005). Many deposits that we now understand as stratigraphic units were not named in association with a type-section but were named for the deposits associated with a common geomorphic feature such as an uppermost elevation, and contain genetically related sedimentary deposits in the subsurface (i.e. Pamlico of Stephenson, 1912). Stratigraphic names now follow a standardized procedure- the North American Commission on Stratigraphic Nomenclature (2005). No similar, standardized, formal procedure applies to structural features, geomorphic features, or unconformities (which sometimes receive designations). However, geomorphic features (terraces, scarps, toes) in the Atlantic Coastal Plain are closely allied to surficial stratigraphic units (formations) and have proved very useful for understanding and describing much of the geology at the surface. In order to keep the terminology understandable in using names for terraces and scarps, workers generally and informally follow the "rule of priority" in parallel with the usage in the various and current stratigraphic codes. In some cases one name has been applied to both a formation (a stratigraphic unit) and its associated terrace (a geomorphic feature). In other cases, a name given to a terrace closely resembles the name given to a formation that does not underlie the terrace with the similar name. No conflict in priority would apply or is recognized in either event, however, because geomorphic names and stratigraphic names apply to different kinds of features or concepts. Names of easily or widely recognized geomorphic features are capitalized (Appalachian Mountains, Atlantic Coastal Plain) and names of scarps (Orangeburg Scarp, Parler Scarp) are in this category.

Sequence Stratigraphy

Sequence stratigraphy, a branch of sedimentary stratigraphy, uses the order in which contemporaneous strata accumulated, along with a framework of major depositional and erosional surfaces to interpret the depositional setting of clastic and carbonate sediments from continental, marginal marine, basin margins and down-slope settings of basins. The framework surfaces that bound and subdivide the contemporaneous strata were often generated during changes in relative sea level and formed during associated deposition and erosion (Catuneanu et al., 2011). System tracts relate the organization of sediment packages to changes in the base level of erosion (Baum and Vail, 1988). A Transgressive Systems Tract (TST) is a package of deposits that accumulate as the result of a rise in sea level. A Highstand Systems Tract (HST) is the package of deposits that accumulate immediately after the transgression and are associated with the highest point of sea level. The lower bounding surface of a TST is the Transgressive Surface of Erosion (TSE), which marks the base of the rise in sea level at a given location. TSE’s are the basal unconformities of Pliocene and Pleistocene marine deposits in South Carolina. The lower boundary, i.e. the surface beneath the HST is the Maximum Flooding Surface (MFS). In general, the Sequence Boundary (SB) often is the boundary between coarsening-upward or fining-upward cycles. In the southeastern Atlantic Coastal Plain, commonly the SB is recognized at the change from offshore shelf sand of the HST to somewhat coarser sand in the basal part of the overlying Falling Stage Systems Tract (FSST). FSST is a package of deposits that accumulate during a fall in sea level. In Pliocene and Pleistocene formations at the surface, the SB commonly is at the base of the FSST. The FSST is preserved in some Pliocene and Pleistocene deposits in South Carolina. The Lowstand Systems Tract (LST) is a package of deposits that accumulate during the lowest part of a fall in sea level, or during a stillstand that follows the lowest part of a fall in sea level. No LST deposits are known to occur in Pliocene and Pleistocene onshore deposits in South Carolina (Doar and Kendall, 2014). In general, any LST deposits that correlate with marine terraces would be expected to exist offshore from the present shoreline. Due to the sediment-starved nature of the coast of South Carolina, such LST deposits would have had a high probability of being removed and recycled by erosion during subsequent rises in sea level.

As addressed previously, terraces and scarps are geomorphic terms. A former interpretation of terraces has been that they represent the former sea bottom of the water during the maximum sea level. Current understanding is that the scarp toes represent the top of the maximum sea level or the highest elevation of the accommodation and that the terrace is the intertidal or subaerial surface of the seaward depositional unit (Doar and Kendall, 2014).

The coast of South Carolina is typically a sediment-starved system (Gayes et al., 2002; Gayes et al., 2003; Ojeda et al., 2004). In a sediment-starved setting, marine transgressions erode and redeposit (cannibalize and recycle) pre-existing sediments as opposed to filling the newly cut accommodation space with surplus imported sediments.

Since there is little-to-no surplus sediment to accumulate above the water level, a geomorphically flat terrace results (1-2° incline on the plain – Cronin et al., 1981). Each later transgression cuts its own space, creating a new stratigraphic unconformity, and leaves its own distinct genetically related package of sediments above the unconformity. If a later unconformity bounds these deposits, an alloformation can be produced. If this alloformation is preserved at the surface, and it is similar or lower in elevation than the older deposits, it can have a related terrace and inland scarp (Figure 2.5). Terraces and alloformations then "toe" against older deposits at scarps at the surface and the toe is a reference for maximum sea level during that transgression (Figure 2.6). If the younger sediments are estuarine, then they will approximate mean high tide elevation. If the younger sediments are from the barrier sand or dune fields, then they may be several feet higher than the mean high tide elevation due to eolian processes.

Since we are focusing on marine sediments and deposits, the effects of fluvial process, both erosional and depositional, will not be addressed herein.

METHODS

This study started with a literature search to collate previous work related to the Pliocene and Pleistocene sections of South Carolina and to sort through the various nomenclature, styles, and concepts of mapping by previous workers. Geomorphic boundaries of Pleistocene marine terraces (toes of scarps) in South Carolina were transferred from 1:24,000 South Carolina Geological Survey STATEMAP geological maps, United States Geological Survey (USGS) geological maps, or were delineated from 1:24,000 topographic maps and aerial photographs.

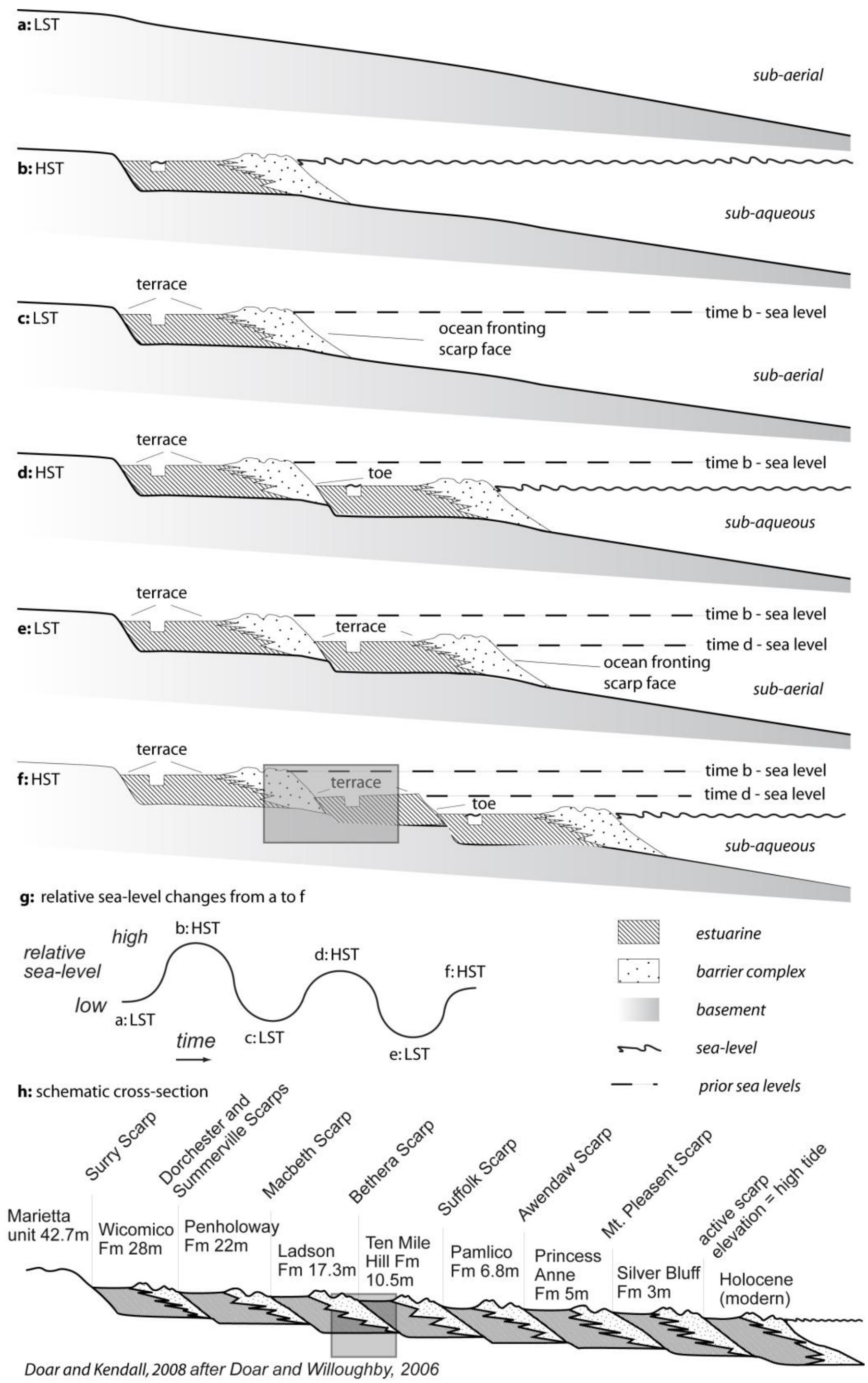


Figure 2.5. Downstepping Highstand Model of the Pleistocene Alloformations of South Carolina.

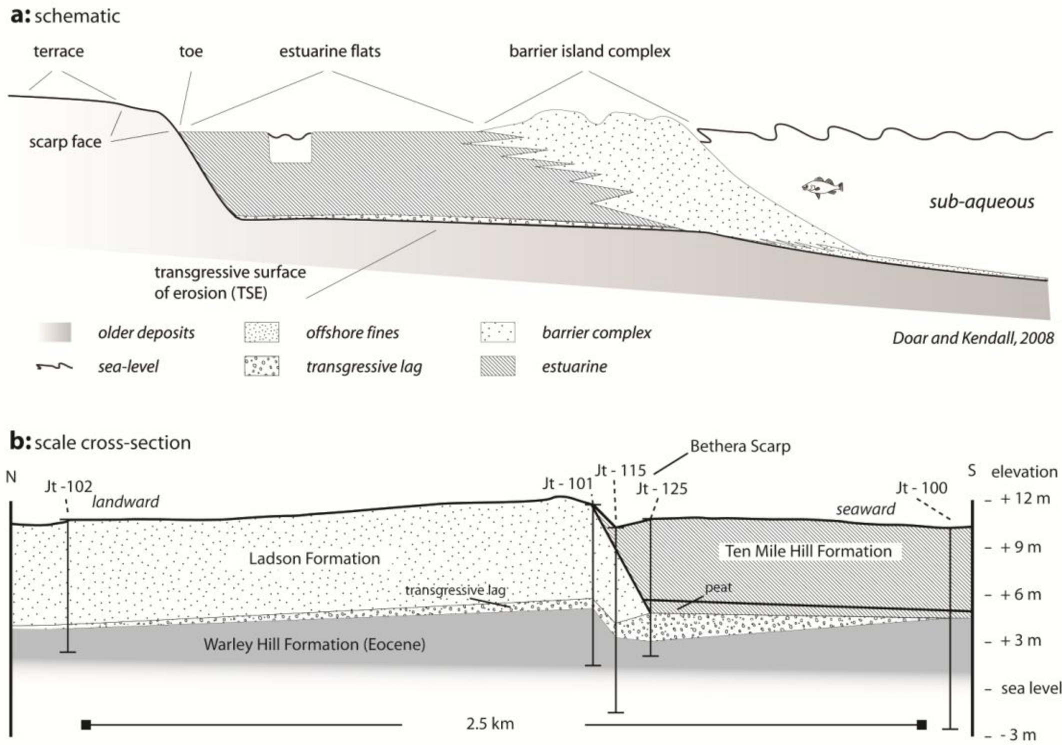


Figure 2.6. Schematic and Actual Cross Section of the Bethera Scarp Near Jamestown, South Carolina.

New geologic mapping, comprised of: field surveys, coring, power-auger drilling, vibra-coring, hand-auguring, inspection of topographic and soil maps, and, more recently, LiDAR images, followed the literature search and geomorphic analysis. The sample collection locations were identified in the field by elevation and geographic location. Samples from surface exposures, and from boreholes, were examined in the field with a 10x loupe magnifier and their position and physical characteristics were logged (e.g. surface elevation, depth, grain size, composition, sorting, rounding, color, induration). The logs were used to interpret the facies associations, unconformities, and the geometry of genetically-related sediments. The borehole logs are on file at the South Carolina Geological Survey. If material collected could be dated using analytical means, such as ^{14}C or OSL (Optically Stimulated Luminescence), then this was analyzed by outside workers as budget allowed. Absolute age dating of the deposits is difficult, often very expensive, and limited. The geochronology referenced is in Table 2.2. Stratigraphic correlations were made by comparing lithological descriptions, determination of the genetically related sediments, bounding surfaces/unconformities, such as the TSE and MFS, and common elevations of those elements with the known geochronology. From these results, geologic maps and subsurface cross sections were produced.

NATURE OF THE ATLANTIC COASTAL PLAIN STRATIGRAPHIC RECORD

General Remarks

Early workers concluded that coastal plain sedimentary deposits resulted from eustatic sea level changes, or fluvial erosion, related to the start or end of four major glacial intervals (Shattuck, 1901 a, 1901 b, 1906; Sloan, 1908; Clark et al., 1912; Cooke,

Table 2.2. Geochronology of the Pleistocene Alloformations of South Carolina. The geochronology is derived from existing publications except for the 2013 data for the Silver Bluff presented herein in Table 2.7.

	Geochronology of the Pleistocene Marine Formations of South Carolina							
Formation	**Scarp**	**Scarp Toe Elevation (m)**	**Assigned age**	**Numerical technique**	**Error range**	**Stratigraphic context**	**Reference**	**Notes**
Marietta unit	Parler	42.6	1.8-2.4 Ma, 2.3 Ma+, 1.6 Ma	Rubidium/Strontium, Planktonic Forams Zone PL5		Correlation with Bear Bluff Formation	McCartan et al., 1982; Markewich et al., 1992; Weems et al., 2011	Correlated with upper part of the Bear Bluff Fm, basal shell lag in NC
Wicomico	Surry	27.4 – 28.9	1.80-2.12 Ma, 1.4-1.6 Ma	Strontium 87/86	(± 150 ky)	Macrofossils	Weems et al., 1997; McGregor, 2011	Older age correlated with Bear Bluff Fm
Penholoway	Dorchester	21.3 – 22.8	730 - 970 ka	Uranium disequilibrium series	10%	Corals	Weems and Lemon, 1989	
Ladson	Macbeth	17.4	400 or 450 ka	Uranium disequilibrium series	10%	Corals	McCartan et al., 1984; Weems and Lemon, 1989	
Ten Mile Hill	Bethera	10.7	200 - 240 ka	Uranium disequilibrium series, Paleontology, Optically stimulated luminescence	10%, range of fossil species overlap, as little as 5%	Corals, Fossils from SC, Sands	Szabo, 1985; Weems et al., 1997; Sanders et al., 2009; Willis, 2006	Referred to as Talbot Formation or terrace in older publications
Pamlico	Suffolk	6.7	90 - 120 ka	Uranium disequilibrium series	10%	Corals	Wehmiller and Belknap, 1982	Younger dates may be the Princess Anne Fm
Princess Anne	Awendaw	5.2	80 - 100 ka	Uranium disequilibrium series, Amino acid racemization, Optically stimulated luminescence	10%, Based on absolute age determinate, as little as 5%	Corals in beach swash zone, Amino acid racemization on bivalves, Quartz sand in beach ridges	York et al., 2001; Wehmiller et al., 2004; Willis, 2006	Two groups of dates- Optically stimulated luminescence - 78-90 ka and 100 ka, Amino acid racemization and U/Th - 80 ka
Silver Bluff	Mt. Pleasant	3.0	34 ka, ≥30 ka, 100 ka, ***40-20 ka***	Carbon 14, Carbon 14, Optically stimulated luminescence	As little as 5%, ± 1830	Peat deposits, Quartz sand in beach ridges	Hoyt and Hails, 1974; Weems and Lemon, 1993; Zayac, 2003; ***This paper Table 7***	Alloformation mapped between Princess Anne alloformation and Modern deposits

1930 a; 1930 b). Since World War II, improvements in topographic maps, subsurface research, and deep-sea stratigraphy have provided evidence for many more than the four major glacial intervals that altered sea level during the Pleistocene (Imbrie, 1984; Shackleton, 1987; Krantz and others, 1996).

Correlations among terraces, scarps, and formations from state to state along the east coast of North America have varied. In South Carolina no fewer than 15 different workers have proposed names and correlations. In this paper the history of that work addresses scarps, then terraces, and then formations.

Note: all elevations within the body of this text are in meters with feet included in parenthesis owing to the historical nature of the work.

History of Work- Pliocene to Pleistocene Deposits

Geomorphology

Scarps

Some, but not all, workers assigned names to the scarps associated with marine terraces. Johnson (1907) and Wentworth (1930) both referred to scarps, but did not assign names to them. Cooke (1936) and Hoyt and Hails (1974) proposed naming the seaward scarps after the attached landward terrace. Other authors listed in Table 2.3 gave the scarps names independent of the landward terraces, because they recognized that some scarps are cut into sediments of differing ages.

Terraces

Even the first reviews of the geomorphology of the Atlantic Coastal Plain noted the terraces, which denote the surficial expression of the underlying formations. For example,

Table 2.3. Examples of Publications with Scarp Names Independent from Terrace Names. They are listed chronologically with the formation, scarp name (if provided), and scarp toe elevations.

Publication	Formation	Scarp	Toe Elevation
Colquhoun	Silver Bluff	*	+3 m (+10)
(1974)	Princess Anne	Awendaw	+4.6 m (+15)
	Pamlico	Suffolk	+7.6 m (+25)
	Talbot	Bethera	+12.2 m (+40)
	Penholoway	Summerville	+21.3 m (+70)
	Wicomico	Dorchester	+33.5 m (+110)
	Okefenokee	Parlor	+41 m (+135)
Hoyt and	Silver Bluff	*	+1.4 m (+4.5)
Hails (1974)	Princess Anne	*	+4 m (+13)
	Pamlico	*	+7.3 m (+24)
	Talbot	*	+12.2-13.7 m (+40-45)
	Penholoway	*	+21.3-22.8 m (+70-75)
	Wicomico	*	+28.9-30.4 m (+95-100)
Weems	Silver Bluff	Mt Pleasant	+3 m (+10)
(from various	Wando	Awendaw/ Suffolk	+5.2 m (+17)
maps)	Ten Mile Hill	Bethera	+10.7 m (+35)
	Ladson	*	+17.4 m (+57)
	Penholoway	Summerville	+21.3-22.8 m (+70-75)

	Wicomico	Dorchester	+27.4-28.9 m (+90-95)
Doar and	Silver Bluff	Mt Pleasant	+3 m (+10)
Willoughby	Princess Anne	Awendaw	+5.2 m (+17)
(2006)	Pamlico	Suffolk	+6.7 m (+22)
	Ten Mile Hill	Bethera	+10.7 m (+35)
	Ladson	Macbeth	+17.4 m (+57)
	Penholoway	Summerville	+21.3-22.8 m (+70-75)
	Wicomico	Dorchester	+27.4-28.9 m (+90-95)
Doar and	Silver Bluff/Tabb- Poquoson mbr		+3 m/ 2.2 m (+9.8 ft/ 7.2 ft)
Berquist	Princess Anne/Tabb- Lynnhaven mbr		+5.2 m/ 5.5 m (+17 ft/ 18 ft)
(2009)	Pamlico/Tabb- Sedgefield		+6.7 m/ 8.5 m (+22 ft/2 8 ft)
SC/VA	Ten Mile Hill		+10.7 m (+35 ft)
	Shirley		+14.6 m (+48 ft)
	Ladson/Chuckatuck		+17.4 m/ 17.4 m (+57 ft)
	Penholoway/Charles City		+21.4 m/ 23.1 m (+70 ft/ 76 ft)
	Wicomico/Windsor		+27.5 m/ 28.9 m (+90 ft/ 95 ft)
Doar and	Silver Bluff	Mt Pleasant	+3 m (+10)
Kendall	Princess Anne	Awendaw	+5.2 m (+17)
(2014)	Pamlico	Suffolk	+6.7 m (+22)
	Ten Mile Hill	Bethera	+10.7 m (+35)

Ladson	Macbeth	+17.4 m (+57)
Penholoway	Summerville	+21.3-22.8 m (+70-75)
Wicomico	Dorchester	+27.4-28.9 m (+90-95)
Marietta	Parler	+42.3 (+145)

“*” indicates scarps not named

the *Talbot terrace* was the flat surface atop the *Talbot Formation*. A partial list of authors who used terrace names is included in Table 2.3. They are listed in order of descending elevation.

Coharie

The Coharie was named for Great Coharie Creek, a tributary of Black River in NC (Stephenson, 1912). The terrace plain formed by the surface of the formation has a widespread development on either side of the narrow valley of this creek in the northern half of Sampson County, NC (Stephenson, 1912; Daniels, Gamble, Wheeler and Nettleton, 1966). Its landward limit is the Orangeburg Scarp, variably at +70.1 to 54.9 m (230 to 180 ft) because its elevation has been greatly modified by warping or tilting of the land surface since its formation (Winkler and Howard, 1977). Its seaward limit is the Parler Scarp (Colquhoun and Duncan, 1964, 1966) at ~ +42.7m (+140 ft).

Argyle

The *Argyle* was named for the community of Argyle, Clinch County, Ga for a terrace with a landward limit of +53.3 m (175 ft) and a seaward limit of + 45.7 m (150 ft) (Huddlestun, 1988). This landward elevation is close to the elevation of the Orangeburg Scarp across the Savannah River in SC (Doar, 2012) and the seaward limit is comparable to the Parler Scarp.

Sunderland

The *Sunderland* was named for the hamlet of Sunderland, Calvert County, Md. (*Sunderland Formation*-Shattuck, 1901 a; *Sunderland Terrace*-Cooke 1930 a, 1930 b, 1931) for the deposits landward of the Wicomico terrace and seaward of an alleged but not since confirmed scarp at 36.6 m (120 ft) elevation.

Okefenokee

The *Okefenokee* was named for the Okefenokee Swamp in Ga. (Stephenson, 1912). The landward limit in Ga is a shoreline at +45.7 m (150 ft) and its seaward limit is the elevation of a shoreline at +30.4 m (100 ft). These shorelines (scarps) were not given a name but are comparable to the Parler and Surry scarps respectively. These elevations are comparable to the bounding elevations of the Lakeview terrace in South Carolina.

Lakeview

The Lakeview (informally named "Lakeview surface" by DuBar et. al., 1974) is named for Lakeview, Dillon County, SC. The landward limit of the Lakeview terrace is the toe of the Parler Scarp (Colquhoun and Duncan, 1964, 1966), or *Mechanicsville Scarp* (DuBar et al., 1974), at ~ +42.7m (+140 ft). The seaward limit of the Lakeview is the toe of the Surry Scarp, at ~ + 28 m (+95-90 ft) (Johnson, 1907; Flint, 1940; DuBar, 1971).

Wicomico

The Wicomico was named for the Wicomico River, St. Mary's and Charles counties, Md. (Shattuck ,1901 a; 1901 b). Its landward limit is the Surry Scarp at +27.4 m (90 ft) and its seaward limit is the Dorchester Scarp at + 21.3 m (70 ft) (Colquhoun 1962; 1965; 1969 b).

Penholoway

The Penholoway was named for Penholoway Bay and Creek, Wayne County., Ga. (Cooke, 1925). In SC its landward limit has been considered to be the Dorchester Scarp at + 21.3 m (70 ft) and its seaward limit was called the *Summerville Scarp* at + 12.8 m (42 ft) (Colquhoun et al., 1991). Doar and Willoughby (2006) revised this assignment because they could find no scarp at 12.8 m. they concluded that the alleged scarp was misidentified on older, less accurate maps, and that the observed seaward border actually has an elevation similar to the Dorchester Scarp seaward of the Penholoway. The Macbeth Scarp at +17.4 m (57 ft) (Doar and Kendall, 2014) is now considered to be the seaward limit of the Penholoway.

Chowan

The *Chowan* was named for the Chowan River, in NC (Clark et. al., 1912; Richards, 1950). The *Chowan* is an upper subdivision of Shattuck's *Talbot* actually separate from the Pamlico. The area is between +18.3 m (60 ft) and +9.1 m (30 ft) in elevation. The *Chowan* was informally designated the *Cordesville terrace* in SC (Willoughby and Doar, 2006), before the equivalent and earlier named *Chowan* was researched, and now is abandoned. The landward limit is the Macbeth Scarp at +17.4 m (57 ft) and the seaward limit is the Bethera Scarp at +10.67 m (35 ft) (Doar and Willoughby, 2006).

Talbot

The *Talbot* was named for Talbot County, Md., in the area between +15.2 m (50 ft) and 12.2 or +9.1 or 12.2 m (40 or 30 ft) in elevation (Shattuck, 1901 a). There are actually two surfaces in this area that have been referred to as the *upper and lower Talbot* in SC (Colquhoun, 1965; 1974). The Bethera Scarp, which toes at +10.67 m (35 ft) elevation, named by Colquhoun (1965; 1969 a), is in the middle of the terrace and separates the upper and lower terraces (Colquhoun et al., 1972). The *Talbot's* landward extent was the *Summerville Scarp* +12.8 m (42 ft) as defined by Colquhoun (1965; 1974) and its seaward extent was the Suffolk Scarp at + 6.7 m (22 ft).

Pamlico

The Pamlico was named for Pamlico Sound, eastern NC (Stephenson, 1912). The inland extent is the Suffolk Scarp at + 6.7 m (22 ft) and its seaward extent is the Awendaw Scarp at + 5.8 m (17 ft).

Princess Anne

The Princess Anne was named from typical exposures at the village of Princess Anne, Princess Anne County, eastern Va. (Wentworth, 1930). Its inland extent is the Awendaw Scarp at + 5.8 m (17 ft) and its seaward extent is the Mt. Pleasant Scarp at +3 m (10 ft).

Silver Bluff

The Silver Bluff was named for the Silver Bluff notch in Dade County, Fl. (Hoyt and Hails, 1974). Its inland extent is the Mt. Pleasant Scarp at + 3 m (10 ft) and its seaward extent is current Mean High Water.

Holocene

Modern coastal processes are building and modifying the terrace currently under construction. Since its formation is a result of the current transgression, and it will not be completed until the next regression, its final geomorphic form has not been set and has not been named.

Geology

Subsurface stratigraphic units

The term terrace cannot be used for features in the subsurface since it is a geomorphic term. If surficial sediments of a marine incursion, or relative highstand, are abandoned by a subsequent drop in relative sea level and then become covered by the sediments of a younger marine incursion separated by a recognized unconformity, then the stated marine sediments constitute a separate subsurface stratigraphic unit (formation). We now discuss the units only recognized in the subsurface.

Goose Creek Limestone

This unit was first described by Tuomey (1848), named as the Goose Creek marl/phase by Sloan (1908), abandoned by Cooke (1936), revived and formally named the Goose Creek Limestone by Weems and others (1982), and revised by M. R. Campbell (1992) for quartzose, moldic limestone and calcarenite of early Pliocene age; older than the Raysor Formation (Weems et al., 1997) and the Duplin Formation (M.R. Campbell, 1989, 1992; M.R. Campbell and L.D. Campbell, 1995).

Raysor Formation

The Raysor was named the Raysor marl by Cooke (1936) for dark-blue calcareous sands near Raysor's Bridge, Colleton County, SC., revised and formalized by Blackwelder and Ward (1979), and revised multiple times since (Ward and Huddleston, 1988; Cronin, 1991; Markewich and others, 1992; M.R. Campbell and L.D. Campbell, 1995). It consists of very shelly quartz sand to soft, dark-greenish gray, glauconitic and phosphatic beds (Weems et al., 1997).

Pringletown beds

The Pringletown was informally named by Weems and Lemon (1996) to accommodate subsurface strata, no more than 3 m (10 ft) thick, that overlie the Raysor Formation and underlie the Waccamaw Formation. They consist of dark bluish-gray to dark-gray sandy, micaceous clay and clayey fine-grained quartz sand.

Wabasso beds

The Wabasso was named by Huddlestun (1988) for deposits in a narrow belt of lower Pliocene deposits that cross the Savannah River into South Carolina. Huddlestun (1988) described them as phosphatic and calcareous sand with intermittent clay beds. They are possibly correlative to the Duplin Formation (Woolsey, 1976).

lower Waccamaw Formation, lower beds at Windy Hill, lower beds at Calabash

The name lower Waccamaw Formation was used by Cronin et al. (1984) for deposits containing the same faunal association as the deposits J. R. DuBar worked on at Old Dock, Columbus County, NC, but not the same those included in the stratotype Waccamaw Formation. The lower beds at Windy Hill, Horry County, SC and at Calabash, Brunswick County, NC were identified by Campbell and Campbell (1995) as having a faunal assemblage essentially identical to the lower Waccamaw Formation. The Windy Hill deposits overlie the Upper Cretaceous Peedee Formation and include reworked fossils from the Duplin Formation.

Waccamaw Formation

The Waccamaw was named Waccamaw beds by Dall and Harris (1892) for a fossiliferous exposure along the Waccamaw River in Horry County, SC. It is composed of deposits that lie entirely east of the Surry Scarp (Johnson and DuBar, 1964). The type section of the Waccamaw Formation is a lagoonal facies (DuBar et al, 1974) that underlies a younger terrace and therefore cannot be directly correlated an associated terrace. It consists of unconsolidated gray and buff fine quartz sand that can be conglomeratic or phosphatic (Clark and Miller, 1912). It has been assigned to Miocene and Pliocene ages based on fossils (Sloan, 1908), revised to Pleistocene by Akers (1972) and

DuBar et al. (1974). Graybill et al. (2009) and McGregor et al. (2011) have confirmed a Pleistocene age of 2.12-1.5 Ma.

Daniel Island beds

The Daniel Island was named by Weems and Lemon (1988; 1996) in the Ladson Quadrangle for backbarrier deposits that underlie the Penholoway Formation. They consist of dense clay and sand with minor phosphate sand and pebbles, scattered fine mica flakes, and may contain shells or shell fragments.

Wadmalaw Marl

Sloan (1908) named the Wadmalaw marl for a deposit that overlies the Miocene Edisto marl and underlies the Bohicket marl-sands. It is 1.2 m (4 ft) or less in thickness.

Bohicket Marl-Sands

Sloan (1908) named the Bohicket marl-sands for beds that overlie the Wadmalaw marl south of Ten Mile Hill, Charleston County, SC. It is 3 m (10 ft) or less in thickness.

Accabee Phosphate Gravels

Sloan (1908) named the Accabee phosphate gravels in the Charleston phosphate district for a deposit that occurs intermittently. This gravel overlies Oligocene deposits and the Bohicket marl-sands in the Charleston area and has a thickness of 1.2 m (4ft) or less.

Horry Clay

The Horry clay was named by Cooke (1936) for clay along the Intracoastal Waterway in Horry County, SC. It consists of light brown slightly silty clay. This unit may correlate to the informal Pine Island clay of DuBar (Myrtle Beach quadrangle borehole logs, not published but on file at SCGS) mined by Waccamaw Pottery/Brick Company along the Intracoastal Waterway around US HWY 501.

Mixed surficial and subsurface stratigraphic units

Duplin Formation

The Duplin was named Duplin beds by Dall (1896) and formalized by Clark and Miller (1912) for exposures in Duplin County, east-central NC, especially in Natural Well, southwest of Magnolia, NC. This name is used for deposits seaward of the Orangeburg Scarp and landward of the Parler Scarp in SC. It consists of unconsolidated sand, arenaceous clay, and shell marls (Clark and Miller, 1912).

Okefenokee Formation

The *Okefenokee* was named for sediments that underlie the *Okefenokee terrace* in SC and overlie the Duplin Formation east of the Parler Scarp by Colquhoun and Duncan (1964). They recognized two members; Holly Hill and Eutawville. The Holly Hill Member consists of orthoquartzitic to subarkosic, micaceous, quartz sand and gravel, with variable bedding including scour-and-fill channels. The Eutawville Member overlies the Holly Hill Member and is composed of light gray, poorly sorted, rarely micaceous, clayey, fine-grained quartz sand with rare coarse-grained quartz sand and granules. With no geological correlation to the Okefenokee area of Georgia, we feel that a locally-derived formation name should be applied.

Bear Bluff Formation and Marietta unit

With the revision of the age of the base of the Pleistocene (and of the Quaternary) from 1.866 Ma (Berggren and others, 1995) to 2.588 ma (Gibbard and Head, 2009), the stratigraphic unit in South Carolina variously known as the *Bear Bluff Formation*

(DuBar, 1969; 1971; Owens, 1990) or the congruent Marietta unit (DuBar, 1971), both formerly considered of Pliocene age, are now considered early Pleistocene.

DuBar (1971) informally proposed the *Bear Bluff* as a formation. Subsequently DuBar et al. (1974) formally named the *Bear Bluff Formation* and placed its type section at Bear Bluff in Horry County, SC, in the present Nixonville 7.5-minute quadrangle. This name has been applied to a sequence of 'calcareous sandstones, sandy limestones, subarkosic sand, and calcareous silts' in southeastern NC. Owens (1990) mapped the *Bear Bluff Formation* extensively at the surface in northeastern SC and southwestern NC, and he considered *the Bear Bluff Formation* to be of late Pliocene age on the basis of fossils from the lower part of the formation at Elizabethtown, NC (L. W. Ward, written communication. cited by Owens, 1990) and of ostracodes from the formation at various places (Cronin and others, 1984); however, the basal part of the *Bear Bluff* type section includes a molluscan fauna that correlates with the lower Pliocene Goose Creek Limestone (M. R. Campbell, 1989, 1992; M. R. Campbell and L. D. Campbell, 1995). The Goose Creek Limestone occurs at various places in the subsurface of northeastern SC and is mined locally (Campbell and Campbell, 1995); its lateral continuity and extent are poorly known. The basal, moldic, fossiliferous, calcareous sediments in the basal *Bear Bluff* type section are separated unconformably from the overlying, quartzose sediments, which extend to the surface.

The Goose Creek limestone, described by Tuomey (1848), named Goose Creek phase by Sloan (1908), formalized by Weems and others (1982), has been assigned as the subsurface equivalent of the *Bear Bluff Formation* and supercedes the *Bear Bluff* in the USGS stratigraphy (M. R. Campbell, 1992). M. R. Campbell (1992) recommended that the *Bear Bluff Formation* be abandoned and we agree. Owens (1990) extensively mapped quartzose sediments found in the upper part of the *Bear Bluff* type section that were assigned a late Pliocene age (Ward et al., 1991; Berggren et al., 1995) or early Pleistocene age (after Gradstein et al., 2004). Due to the proposed abandonment of the *Bear Bluff*, and the age assignments that are now included in the early Pleistocene, these sandy sediments are here assigned to the informal Marietta unit of DuBar (1971) and of DuBar et al. (1974).

The informal Marietta unit was named by DuBar (1971) for the town of Marietta in Robeson County**,** NC. The Marietta unit is composed of the sandy sediments underlying the "Lakeview surface" in Lakeview, Dillon County, SC (DuBar et. al., 1974). Thus, the toe of the Parler Scarp (or *Mechanicsville Scarp*), where preserved, is the landward limit of the Marietta unit.

The informally named Marietta unit of DuBar (1971) is accepted as a valid, albeit informally named, stratigraphic unit, with its informal "type area" at Marietta in the Fair Bluff, SC 7.5-minute quadrangle, Robeson County, southeastern NC. The deposits range from mixed fluvial sand, estuarine mud and sand, and marine barrier complexes. We propose that the *Okefenokee Formation* of Colquhoun and Duncan (1964) should be abandoned and its sediments be assigned the local name of Marietta. Since the Holly Hill and Eutawville members of the *Okefenokee Formation* lithologically are not similar to the Marietta unit of DuBar (1971), we consider them as different and valid facies of the same depositional episode and should be kept even though they may only be of limited geographic extent.

Wicomico Formation

The Wicomico was named for the Wicomico River, Maryland, in the area is between +27.4 m (90 ft) to +15.2 or 12.2 m (50 or 40 ft) in elevation (Shattuck, 1901 a). This was revised by Cooke (1931) and is the name applied to the materials under the Wicomico terrace. The Wicomico's inland extent is the Surry Scarp and is traced from Va to Ga (Colquhoun, 1974). Colquhoun (1965; 1974; Colquhoun et al., 1991) interpreted the Surry Scarp as having been formed by a highstand at +27.4 m (90-95 ft) elevation and as marking the boundary between Pliocene sediments and the Pleistocene Wicomico terrace. The area above this scarp is now considered to be early Pleistocene. Terrace width varies from 2 to 20 miles when measured normal to former shorelines (Cooke, 1936; Colquhoun, 1965; 1974; Colquhoun et al., 1991; Doar and Kendall, 2014). The surface deposits range from mixed fluvial sand, estuarine mud and sand, and marine barrier complexes to offshore marine sand.

Penholoway Formation

The Penholoway was named for Penholoway Creek and Bay, Brantley County, Ga. (Cooke, 1925). It consists of fine sand, sandy loam, and dark-gray pebbly sand. The Penholoway's inland extent is the Dorchester Scarp (Colquhoun 1962; 1965; 1969 b). Colquhoun (1962) interpreted the Dorchester Scarp as having been formed by a highstand at +21.5 m (75 ft) elevation and as marking the boundary between the Wicomico and Penholoway terraces. The toe of the scarp is at +21.3 m (70 ft) elevation and the terrace width varies from less than 1 mile to 7 miles when measured normal to former shorelines. It is traceable from NC to Ga (Cooke, 1936; Colquhoun, 1965; 1974; Colquhoun et al., 1991; Doar and Willoughby, 2006; 2008). The surface deposits range from estuarine mud and sand to marine barrier complexes.

Talbot Formation

The *Talbot* was named for Talbot County, Md. (Shattuck, 1901 a), in the area between to +15.2 m (50 ft) and +12.9 or 9.1 m (40 or 30 ft) in elevation and is applied to the sediments under the terrace. Cooke (1931) restricted the *Talbot* to the deposits above a scarp at +12.0 m (25 ft) elevation. These sediments are referred to as the *Talbot Formation* in Md (Shattuck 1901a; 1906), *upper and lower Talbot* in SC (Colquhoun, 1965; 1974) and the *Talbot Formation* in Ga (Hoyt and Hails, 1974). An upper depositional limit was recorded at +13.7 to 12.9 m (45-40 ft) in Ga (Hoyt and Hales, 1974) and in SC (Cook, 1936; 1945) at +12.8 m (42 ft) (Colquhoun, 1974). The terrace width varies from less than 1 mile to 15 miles when measured normal to former shorelines (Cooke, 1936; Colquhoun, 1965; 1974; Colquhoun et al., 1991). The surface deposits range from mixed fluvial sand, estuarine mud and sand to marine barrier complexes. A middle Pleistocene age of 400-200 ka has been established based on coral (U/Th) dates (McCartan et al, 1984).

Later work has proved that the upper and lower *Talbot terraces* overly two units, at 460,000 and 200,000 yrs (Weems and Lemon, 1984 a; 1984 b) equivalent to the Ladson Formation and Ten Mile Hill Formation (Corrado et al., 1986; Doar and Kendall, 2014). The *Talbot's* inland extent was the *Summerville Scarp* as defined by Colquhoun (1965; 1974) who interpreted a scarp at this elevation formed by a highstand at +12.8 m (42 ft) and marking the boundary between the Penholoway and *Talbot terraces*. The Bethera Scarp, which toes at +10.67 m (35 ft) elevation was named by Colquhoun (1965; 1969 b);

it is in the middle of the terrace (Colquhoun et al., 1972). Later work with more accurate maps has proved that there is no stratigraphic break at 12.8 m elevation. Rather it is at +21.3 m (70 ft), which requires a redefinition of the *Summerville Scarp*. That redefinition of the scarp nullifies the upper boundary of the *Talbot* as defined in SC. Later work has proved that the Bethera Scarp is not in the middle of the *Talbot* but separates the Ladson and Ten Mile Hill formations in SC.

Cypresshead Formation

The *Cypresshead* was named for Cypresshead Branch in Wayne County, Ga. (Huddlestun, 1988) for deposits seaward of the Orangeburg Scarp and landward of the landward extent of the Pamlico terrace. It overlies Miocene deposits and includes deposits that were formerly assigned to the Duplin Formation, Marietta unit, Wicomico, Penholoway, and *Talbot* formations. It is composed of fossil-poor, bioturbated, pebbly, quartzose and arkosic sand.

Ladson Formation

The Ladson was named for the town of Ladson, SC (Malde, 1959) and is applied to the sediments under the *Chowan terrace* of Doar and Berquist (2009). Doar and Willoughby (2006) interpreted the landward limit as the Macbeth Scarp that was formed by a highstand at +18.2 to 17.4 m (60 to 57 ft). The surface deposits range from mixed fluvial sand, estuarine mud and sand to marine barrier complexes.

Ten Mile Hill beds/Formation

The Ten Mile Hill was named informally by Sloan (1908) for the deposits at the community of Ten Mile Hill, Charleston County, SC., and resurrected as the Ten Mile Hill beds (Weems and Lemon, 1984 a). Sanders et al. (2009) has elevated the Ten Mile beds to the Ten Mile Hill Formation. Its landward limit is the Bethera Scarp. It consists of fossiliferous sand, clean sand, and clayey sand and clay. The lagoonal deposits below 10.67 m and above 6.7 m had previously been assigned to the Ladson Formation of Malde (1959).

Canepatch Formation

The *Canepatch* was named for deposits near Canepatch Swamp, Horry County, SC (DuBar, 1971). The *Canepatch Formation* is applied to the sediments in the lower part of an exposure along the Intracoastal Waterway between the US Hwy 501 bridge and Canepatch swamp in Myrtle Beach, SC. DuBar et al.'s (1974) description of the *Canepatch* includes portions of the *Talbot* and Pamlico deposits. Subsequent workers have revised the definition of the *Canepatch* (Cronin, 1980: Soller and Mills, 1991).

Socastee Formation

The *Socastee* was named for the town of Socastee, Horry County, SC (DuBar, 1971), and is applied to the sediments in the upper part of an exposure along the Intracoastal Waterway north of the SC 544 bridge. It was revised by McCartan and others (1984) so that the lower part correlates to their Q3 unit (Ten Mile Hill beds of Weems et al., 1997) and the upper part correlates to their Q2 unit (Pamlico Formation of Cooke, 1936). The areal extent of the *Socastee Formation* includes portions of the previously discussed *Talbot* and Ten Mile Hill formations, the Pamlico Formation, and portions of the Princess Anne and Silver Bluff formations.

Pamlico Formation

The Pamlico was named for Pamlico Sound, NC (Clark, 1909, *in* Clark et al., 1912) and is applied to fine sand and blue or gray clay found under the terrace. The Pamlico's landward extent is the Suffolk Scarp (Wentworth, 1930) and the *Cainhoy Scarp* (Colquhoun, 1965). Wentworth (1930), Cooke (1936), and Colquhoun (1965; 1974; Colquhoun et al., 1991) interpreted the Suffolk and *Cainhoy* scarps as formed by a highstand at +7 to 6 m (25-20 ft) elevation and as marking the boundary between the *Talbot* and Pamlico. The toe of the scarp is at +6.7 m (22 ft) (Doar and Willoughby, 2006; Doar and Berquist, 2009; Doar and Kendall, 2014) with an upper limit of +12.2 m (40 ft) on the scarp face (Hoyt and Hails, 1974). The deposits range from estuarine mud and sand to marine barrier complexes. The terrace width varies from less than 1 mile to 20 miles when measured normal to former shorelines and is traceable from NC to Ga.

Sea Island Loams

Sloan (1908) named the Sea Island loams that occur along a line from McClellanville, SC to the mouth of the Broad River, Beaufort County, SC along a curved zone which approximately conforms to the inland waterway (now named the Intracoastal Waterway). These deposits have since been mapped as part of the Wando, Princess Anne, and Silver Bluff formations.

Princess Anne Formation

The Princess Anne was named for Princess Anne County, Va (Wentworth,1930). The Princess Anne's inland extent is the Awendaw Scarp as defined by Colquhoun (1965). Colquhoun (1965) interpreted the Awendaw Scarp as having been formed by a highstand at +5.2 m (17 ft) elevation and as marking the boundary between the Pamlico and Princess Anne terraces. The toe of the scarp is at +5.2 to 4.6 m (17-15 ft) (Hoyt and Hails, 1974; Doar and Kendall, 2014). The deposits range from estuarine mud and sand to marine barrier complexes. The terrace width varies from less than 1 mile to 15 miles when measured normal to former shorelines and, except where it has been removed by younger high stands north of North Inlet, SC, and is traceable from North Carolina to Georgia.

Wando Formation

The Wando was named for exposures along, and near, the Wando River, SC (Sloan, 1908) and revised by McCartan et al. (1980) and McCartan et al. (1984). It encompasses both the Pamlico and Princess Anne deposits. Sloan (1908) noted that the Wando clays and sands overly the Accabee gravels. It consists of sand, shelly sand, clayey sand, and silty clay.

Silver Bluff Formation

The Silver Bluff shoreline was first noted by Parker and Cooke (1944) and Cooke (1945) for the Silver Bluff notch near Biscayne Bay, Florida. At that location, the wave cut notch is +1.5 m (5 ft) elevation. The Silver Bluff Formation was named by Hoyt and Hails (1974) as the sediments deposited under the terrace formed contemporaneously with the Silver Bluff notch. The Silver Bluff's landward extent is the Mt. Pleasant Scarp as defined by Richards (1950) and Colquhoun (1965). Colquhoun (1965) interpreted the Mt. Pleasant Scarp as having been formed by a highstand +3 to 1.8 m (10- 6 ft) elevation and as marking a boundary between the Princess Anne and Silver Bluff terraces. The toe of the scarp is at +3 m (10 ft) (Colquhoun, 1969 b; Hoyt and Hails, 1974, Doar and Willoughby, 2006; Doar and Kendall, 2014). The terrace width is generally less than one mile. The surface deposits range from estuarine mud and sand to marine barrier complexes.

Satilla Formation

The *Satilla* was named by Veatch and Stephenson (1911) and reintroduced by Huddlestun (1988) for the Satilla River, Camden and Charlton counties, Ga. It overlies Miocene deposits and includes deposits that were formerly assigned to the Pamlico, Princess Anne, and Silver Bluff formations along with the Holocene deposits.

Modern deposits

Waiter Island formation

The Waiter Island was informally named by DuBar et al. (1974) for the deposits of late Holocene age near the NC/SC state line on Waiter Island, SC. The current transgression is producing these deposits with the possibility that an earlier Holocene highstand at +2 to 1 m (Balsillie and Donoghue, 2004; Blum et al., 2001, 2002) previously deposited these sediments and they are being modified. The landward extent is the current active scarp with the toe at Mean High Water. The terrace width varies to less than 1 mile, for materials above mean sea level, to more than 30 miles.

Ocean Forrest peat

The Ocean Forrest was informally named by DuBar (1971) for the former town of Ocean Forrest, now North Myrtle Beach, Horry County, SC, for patchy fresh-water peat, and peaty sand and clay, behind the modern beach. DuBar (1971) notes that ^{14}C dates range from ~6-3 ky bp.

DISCUSSION

One Pliocene and eight Pleistocene highstand deposits and associated scarps, along with Holocene deposits are preserved at the surface in the Middle and Lower Coastal Plains of SC. A synthesis is presented in Tables 2.4 and 2.5. Past research (by many authors) from five Atlantic coast states has produced differing interpretations and several sets of names for those terrace deposits and scarps. This paper seeks to find the commonalities in the differing (author's) publications as they relate to SC. The commonalities between most of the previous researchers is a recognition that there are geomorphic features, scarps and terraces, which are traceable for considerable distances, often from state to state, and these terraces have common geologies and chronologies.

The terrace and scarp-bounded sedimentary deposits have been referred to as terrace-formations (Shattuck, 1901 a; 1901 b; Colquhoun, 1974) and morphostratigraphic units (Oaks and DuBar, 1974), with the scarps separating them on the ocean-fronting edge (Colquhoun, 1965; 1974; Colquhoun et al., 1991). Other authors have used formation names (Shattuck, 1901 a; 1901 b; Hoyt and Hails, 1974; DuBar et. al., 1974). Some workers have defined formations partly by the areal limits of the terraces; others have included more than one terrace (McCartan and others, 1984); others divided genetically related deposits to define new formations (DuBar et. al., 1974; Owens, 1990). These differences have resulted with some confusion in correlations. This confusion also has resulted from the use of surface elevation of the terraces, or average elevations, versus the elevations of the toes of scarps. Because an average surface elevation could mean almost anything, the toe of the inland scarp, as defined herein as directly related to the maximum highstand, is used for the relative sea-level elevation. For example, if the terrace at one location is covered with a dune field, the average elevation there will be higher than the same terrace from the same sea level highstand at a location without dunes. However, the toe of the inland scarp will be at a (nearly) consistent elevation because the maximum

Table 2.4. Relative Age Correlations for Deposits Seaward of the Orangeburg Scarp.

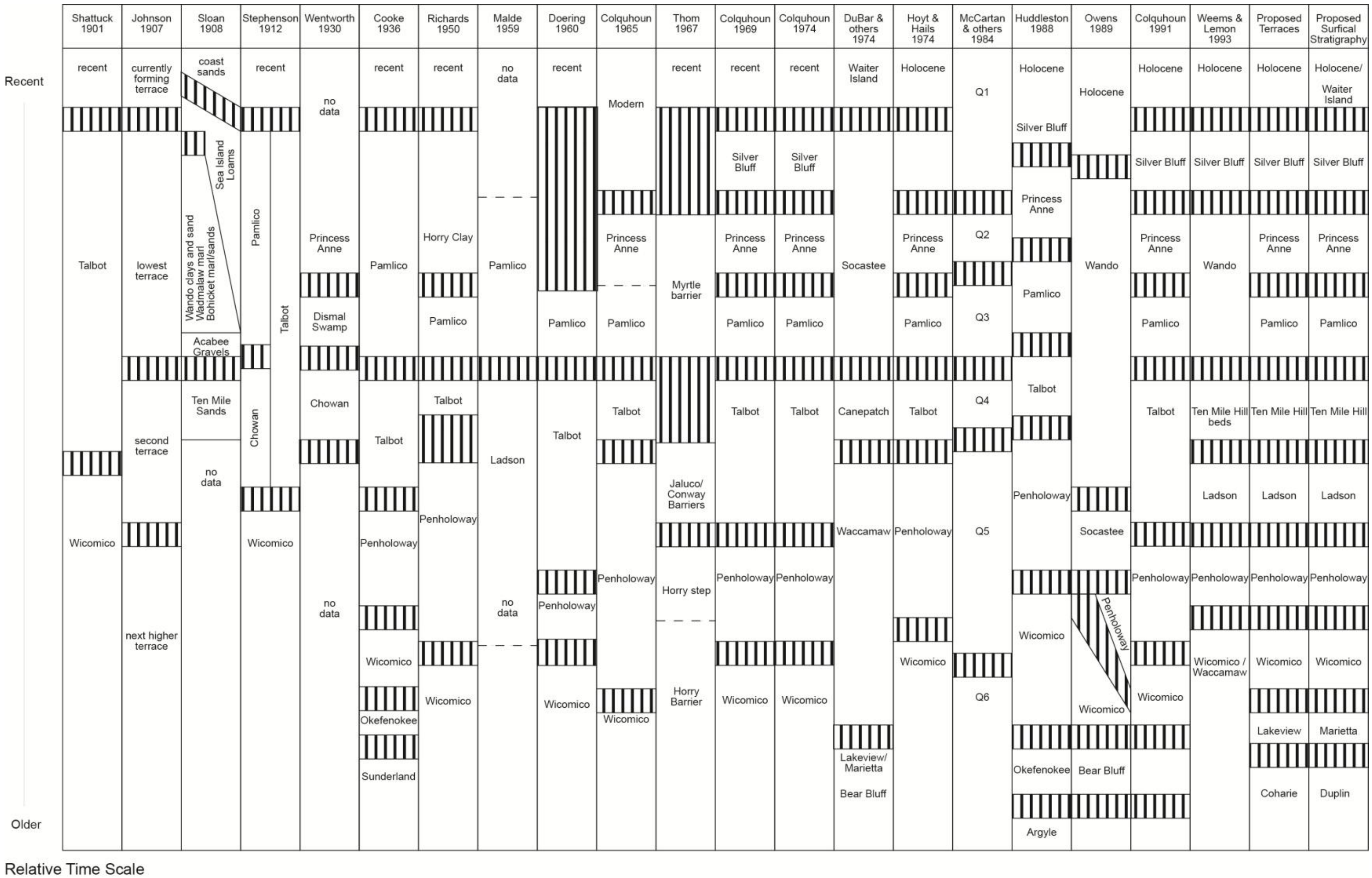
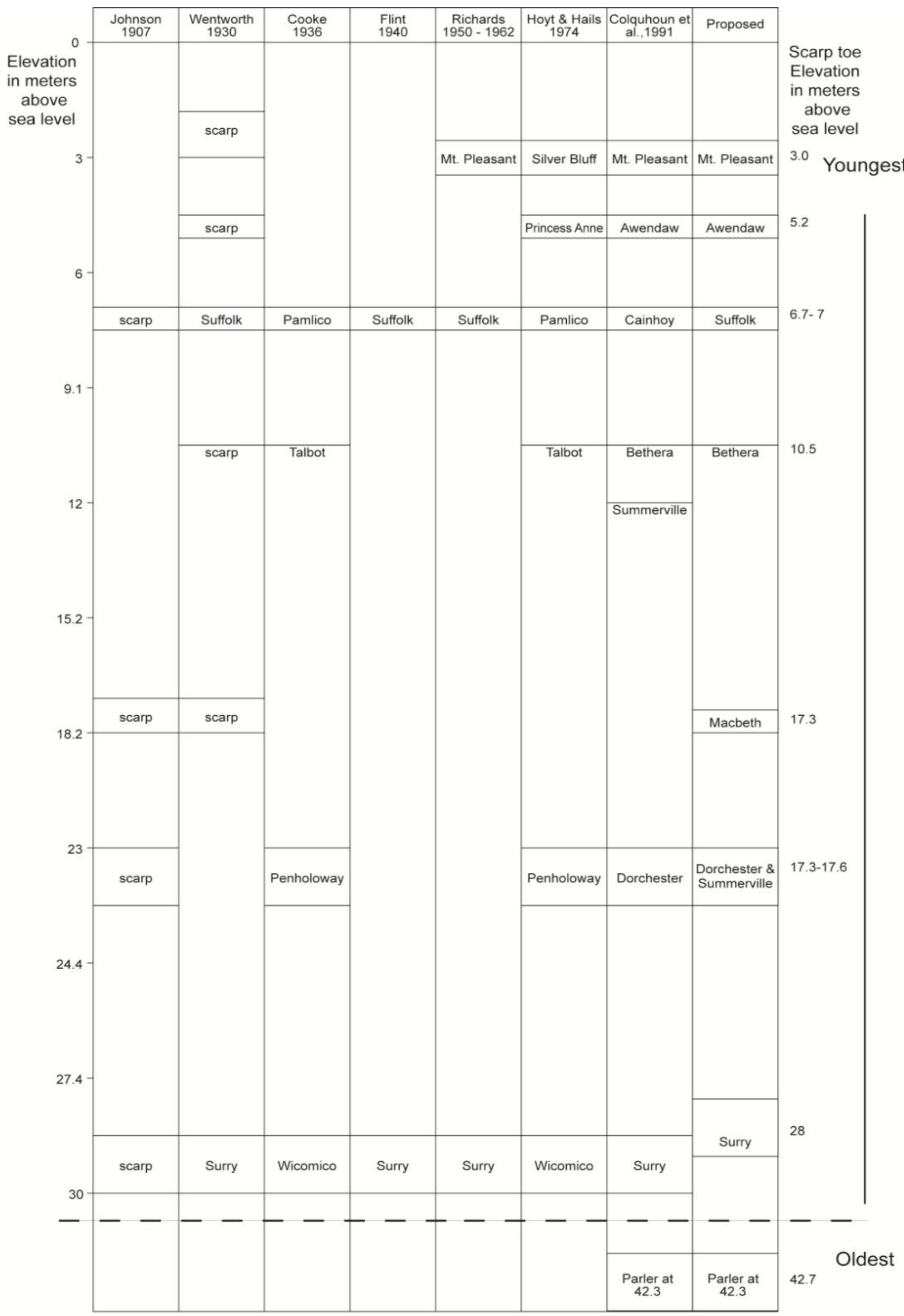


Table 2.5. Correlation of Scarps Seaward of the Orangeburg Scarp.



modified from Doar and Wiloughby, 2006 sea level will generally flood to the same general elevation. The confusion over nomenclature has reached a point that the workers in Virginia abandoned the pre-existing terminology in its entirety (Johnson and Berquist, 1989). Owing to the complexity added by fluvial incision of the coastal plain in Ga, Huddleston (1988) advocated the removal of most stratigraphic nomenclature related to, or based on, the geomorphic terraces. DuBar et al. (1974) and Owens (1990) also abandoned the nomenclature and combined sea-level events together and crossed chronostratigraphic boundaries to create 3 marine sedimentary formations from 5 or 6 marine highstand deposits.

Sequence Stratigraphy

In many Sequence Stratigraphic models (Vail, 1977; Van Wagener, 1988) most of the Transgressive System Tract's and Highstand System Tract's are composed of sediment-surplus deposits. In the Lower Coastal Plain of SC this is not the rule. Most of the deposits are relatively thin, less than 20 m, and because each Transgressive System Tract has to cut its own accommodation space and the Highstand System Tract is relatively small, neither is laterally connected to the Falling Stage System Tract or Lowstand System Tract that follow owing to an erosional/hiatal surface offshore. This lack of lateral continuity and the erosion/reworking of previous deposits denies the worker use of traditional Sequence Stratigraphic concepts for full interpretation. For example, very few Lowstand System Tract fluvial deposits are preserved because they are removed by the Transgressive Surface of Erosion. At the landward edge the Transgressive Surface of Erosion merges with the Maximum Flooding Surface. The common marker for position within a Sequence Stratigraphic framework is the Sequence Boundary. In this area a

Sequence Boundary has often been removed by a later Transgressive Surface of Erosion. Therefore we use the Transgressive Surface of Erosion to denote the lower unconformity and the estuarine Maximum Flooding Surface to denote the sea-level maximum that becomes the subaerial unconformity during the following regression. The equivalent surface in the nearshore or estuarine environment is the beach face, where there is no flooded back barrier system, or the top of the estuarine deposits in the back barrier at the peak of the highstand. The overall geometry of the deposits in Figure 2.5 at first glance resembles forced regression (Posamentier et al., 1992). However, the internal geometries of the alloformations are that of transgressions with the TSE or estuarine facies overlying older deposits with contemporaneous barrier island facies overlying those, not offlapping or progradational geometries with barrier island facies overlying contemporaneous offshore facies.

In SC, Pleistocene depositional units are directly related to the geomorphic terraces that they underlie. The highstand that produced the terrace also is responsible for the sediments beneath it. A younger sediment package is identifiable from an older terrace because it typically has either a transgressive lag deposit or freshwater peat or estuarine clay on the contact with the older unit. The younger deposit also pinches out landward at the toe of its inland scarp. In Pleistocene-age sediments, the terraces are preserved because deposition is primarily an offlap pattern with the result that younger highstands have not removed the surficial exposure of older highstand deposits.

A list of regional, marine, terrace and stratigraphic names, with origins, used for the Pleistocene of South Carolina is presented in relative context in Table 2.4. A list of

Pleistocene scarps with names, origins, and elevations used in South Carolina presented in relative context in Table 2.5.

Stratigraphic Revisions

The *Argyle* terrace exists in the same elevation range as the senior term Coharie and we therefore propose abandoning the use of *Argyle* in SC. We have not been able to prove that the *Okefenokee terrace* correlates to the similar elevation Lakeview terrace in SC. Since it is a local name we therefore propose the use the Lakeview terrace until the *Okefenokee terrace* is proven to correlate to SC.

With the confusion over the use of *Talbot* in the nomenclature, and the associated revision of the underlying geology, the upper and lower *Talbot* names are abandoned and this is further explained by Willoughby and Doar (2006).

The *Chowan terrace* name is shared with the Chowan River Formation in NC. Whereas there is no formal conflict with the use of geomorphic terms and geological terms, we propose abandoning the informal *Chowan terrace* in SC and that the Ladson name be used for the terrace associated with the Ladson Formation deposits to parallel the names of other terraces and formations.

Since Sloan's publication of his "phases" in the Catalogue of the Mineral Localities of South Carolina, (1908) many of his units have been extensively mapped and associated with terraces, formations, or alloformations. We propose abandoning the use of his units that have yet to be promoted to formal status. However, we strongly feel that revisiting his work in the future, as the stratigraphic understanding evolves, will continue to yield noteworthy revelations.

The Marietta unit of DuBar (1971) is proposed to replace the use of the *Bear Bluff Formation* at the surface. Campbell's revision of the lower *Bear Bluff* to be equivalent of the Goose Creek and the lack of agreement with the lithologic descriptions of the Marietta unit supports replacement. We also propose abandoning the designation of "unit" and replace it with alloformation.

The Parler Scarp of Colquhoun (1965) is proposed to replace the use of the *Mechanicsville Scarp* of DuBar et al. (1974) as the scarps denote the same feature and the Parler is the senior term.

The seaward extent of the Penholoway Formation is the Macbeth scarp and the former seaward extent was the *Summerville Scarp* as defined by Colquhoun (1962, 1965, 1969 a). This change is necessary because the direct conflict between Colquhoun's 1965 definition of the *Summerville* as the boundary between the Penholoway and *Talbot*, the cross section of that boundary in the same paper, and recent maps with the Ladson Formation between the Penholoway and *Talbot* (Weems and Lemon, 1984b, 1993; Doar, 2004 a; 2004 b; 2010 a; 2010 b; 2010 c). These changes are incorporated into the revised map (Figure 2.7) and stratigraphic column presented herein (Tables 2.4 and 2.6).

The *Summerville Scarp*, at + 12.8 m elevation, was named as the inland extent of the *Talbot* by Colquhoun (1974). As defined, the *Summerville Scarp* is not a valid name because there is no terrace that toes at + 12.8 m elevation in the Summerville, SC area (Weems and Lemon, 1984 a; 1984 b; 1988; Doar and Willoughby, 2006; 2008). This incorrect elevation of + 12.8 m could be the result of less accurate map data available at the time the scarp was named. The Macbeth Scarp (Doar and Willoughby, 2006; this paper) toes above the + 12.8 m elevation, at +17.4 m and the Bethera Scarp toes below at

Table 2.6. Revised upper Cenozoic Surficial Formations.

Alloformation	Landward Scarp	Toe Elevation	Terrace	Notes
modern sediments	mean high water	developing	not named	will become a formation after regression
Waiter Island	mean high water	early Holocene	not named	early Holocene highstand contested
Silver Bluff	Mount Pleasant Scarp	3 m (10 ft)	Silver Bluff	(Wando Formation in part)
Princess Anne	Awendaw Scarp	5.2 m (17 ft)	Princess Anne	(Wando Formation in part)
Pamlico	Suffolk Scarp	6.7 m (22-25 ft)	Pamlico	(Wando Formation in part)
Ten Mile Hill	Bethera Scarp	10.7 m (35 ft)	Talbot	
Ladson	Macbeth Scarp	17.4 m (57 ft)	Ladson	Cordesville terrace is obsolete, abandoned
Penholoway	Dorchester Scarp	23 m (75 ft)	Penholoway	Penholoway estuarine deposits landward limit
Wicomico	Surry Scarp	27.4 m (90 ft)	Wicomico	
Marietta	Parler Scarp	42.3 m (145 ft)	Lakeview Terrace	Mechanicsville Scarp is obsolete, abandoned
Okefenokee	is restricted to Georgia and awaits further mapping			
Duplin Formation	Orangeburg Scarp	190-240 ft	Coharie Terrace	[early or middle Pliocene)

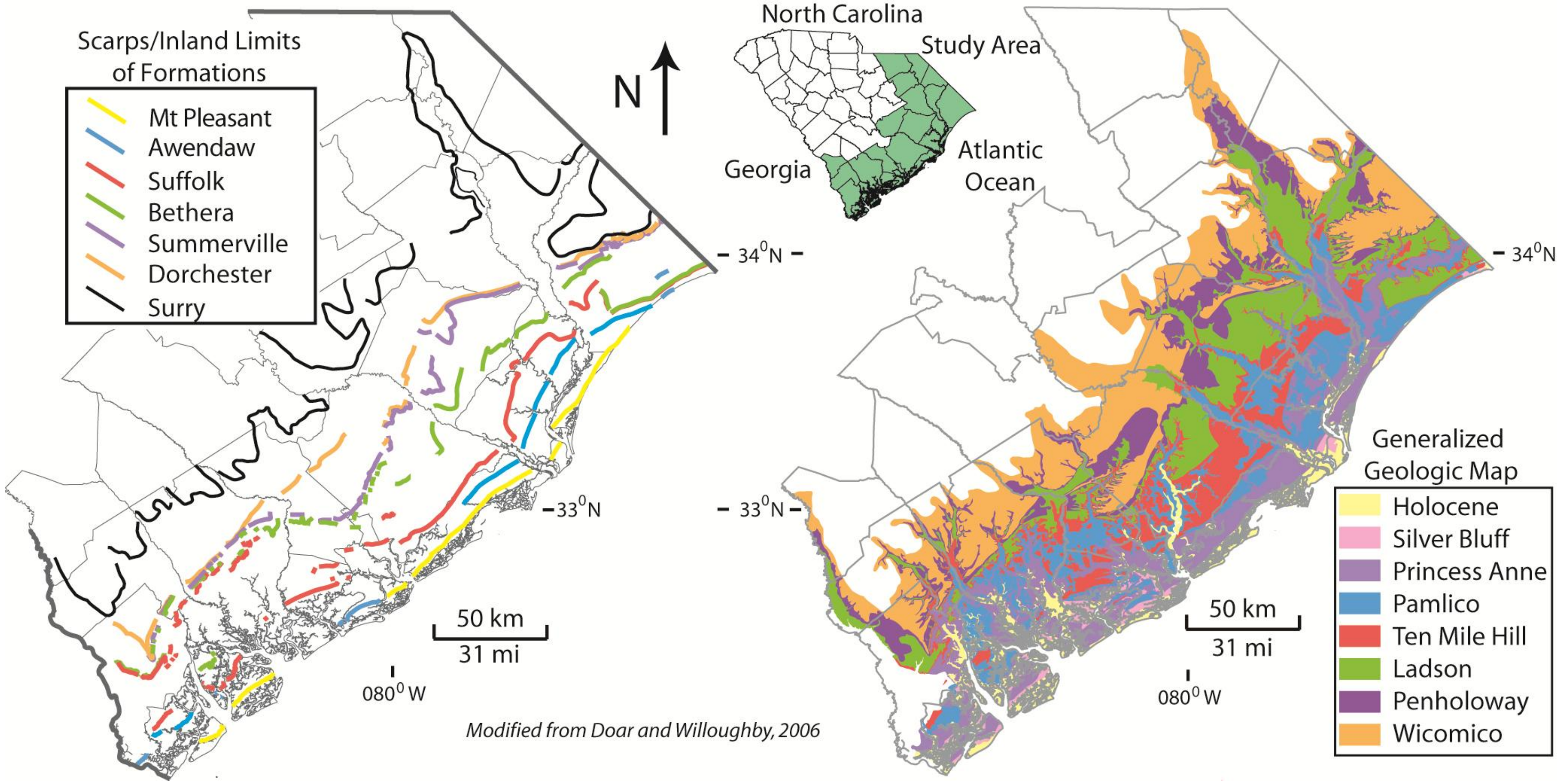


Figure 2.7. Generalized Scarp and Geology Maps of the South Carolina Coastal Plain. These are the surficial deposits seaward of the Surry Scarp.

10.7 m (Colquhoun 1965; 1969 b). These two scarps are the seaward and inland extents of the Ladson terrace (Ladson alloformation) the Ladson Formation of Malde (1959) and the *Chowan terrace* (Clark et. al., 1912; Wentworth, 1930; and Doar and Willoughby, 2006; this paper). Colquhoun at one time recognized that the Bethera Scarp was apparently in the middle of the *Talbot* (Colquhoun et al, 1972) and did not recognize a defined change in lithology across it, so he created the terms “upper” and “lower” *Talbot* to accommodate this. This problem is unfortunate since the *Chowan terrace* in North Carolina occupies similarly higher elevations (Clark et. al., 1912; Richards, 1950) to the *upper Talbot* and previously Malde (1959) had named the Ladson Formation for the deposits under the surface at similar elevations in the Charleston/Ladson area. Weems (1984 a) abandoned the term *Talbot* and chose a historical name similar to a name used by Sloan-Ten Mile Hill sands (1908). There is no terrace in South Carolina that matches Shattuck’s *Talbot* definition (1901 a; 1901 b). The deposits may have existed at one time but have been removed by younger transgressions.

The term *Cainhoy* is a local name given by Colquhoun for the scarp between the Pamlico and *Talbot*; however, Flint (1940) traced the Suffolk Scarp from Suffolk County, Va though NC, SC, and into Ga. As defined, the *Cainhoy Scarp* at +6.7 m elevation is a local name for the more senior term Suffolk Scarp. The Suffolk Scarp is clearly traceable from Suffolk County, Va, into, and across, NC, and into and across SC into Ga. We propose removing the use of *Cainhoy Scarp* and using Suffolk as it is the senior term.

The incised and dissected nature of the Atlantic Coastal Plain deposits in Georgia makes identifying and differentiating alloformations difficult. Huddlestun (1988) notes that there are no terrace- related units composed of discrete or lithologically unique materials from the Duplin Formation age through the younger deposits. He therefore proposed abandoning the prior names related to terraces (*Sunderland*, Wicomico, Penholoway, *Talbot*, Pamlico, Princess Anne, and Silver Bluff) and replacing them with the *Cypresshead* and *Satilla* formations. However, Huddlestun (1988) did not consider the use of alloformations for his stratigraphy, which allows each formation to have similar or identical lithologies since they are defined by their bounding unconformities; therefore we consider the names associated with terraces used prior to Huddlestun (1988) as valid alloformation names.

With the various age dates published for the Silver Bluff, Optically Stimulated Luminescence Data collected in 2013 (Figure 2.8; Table 2.7) support the Marine Isotope Stage 3 age for the Silver Bluff.

Revised Pliocene and Pleistocene, terrace-associated, marine strata of the Middle and Lower Coastal Plains of South Carolina, with descriptions

After review we propose that the existing subsurface unit nomenclature remains intact. The following revisions apply only to units with surficial expression. The descriptions are based on geologic maps prepared by the South Carolina Geological Survey (70 1:24,000 scale maps) and by the U.S. Geological Survey (USGS) (41 1:24,000 scale maps), on their associated borehole logs from the geologic maps (on file at the South Carolina Geological Survey and openfile with the USGS). A sedimentological note: even though it is not explicitly mentioned, all Pliocene and Pleistocene deposits that are in unconformable contact with phosphate-bearing material may contain variable amounts of phosphate sand or gravel reworked from underlying units.

This proposed stratigraphy (Table 2.6) is the result of literature review and the most recent geological mapping of the Pliocene and Pleistocene marine sediments. We are following the North America Stratigraphic Code (NACSN, 2005) by continuing to use prior accepted names where the described formations can be correlated to previous work. In addition, in our use we are revising some of the formations to alloformation status. The use of the informal lower-case “alloformation” with some units indicates that a formalization of the units, to include items such as type section, is in process and not completed.

Duplin Formation

The Duplin was named for exposures in Duplin Co., east-central NC, especially in Natural Well, southwest of Magnolia, NC (Dall, 1898 a; 1898 b). At the landward margin, sediments of the Duplin generally are below the elevation of 75-55 m (245-180 feet) where the deposits overlap, overlie, or abut sediments of Eocene and older deposits of the Upper Coastal Plain at the Orangeburg Scarp. It remains intact with no revisions and is currently the only recognized Pliocene unit at the surface.

Marietta alloformation

Sediments of the Marietta alloformation are generally above the elevation of 27.4 m (90 ft) at their seaward margin where overlapped by the Wicomico alloformation at the Surry Scarp. At the landward margin, sediments of the Marietta generally are below the elevation of 42.7 m (140 feet) where the deposits overlap, overlie, or abut sediments of the Pliocene age Duplin Formation at the Parler Scarp.

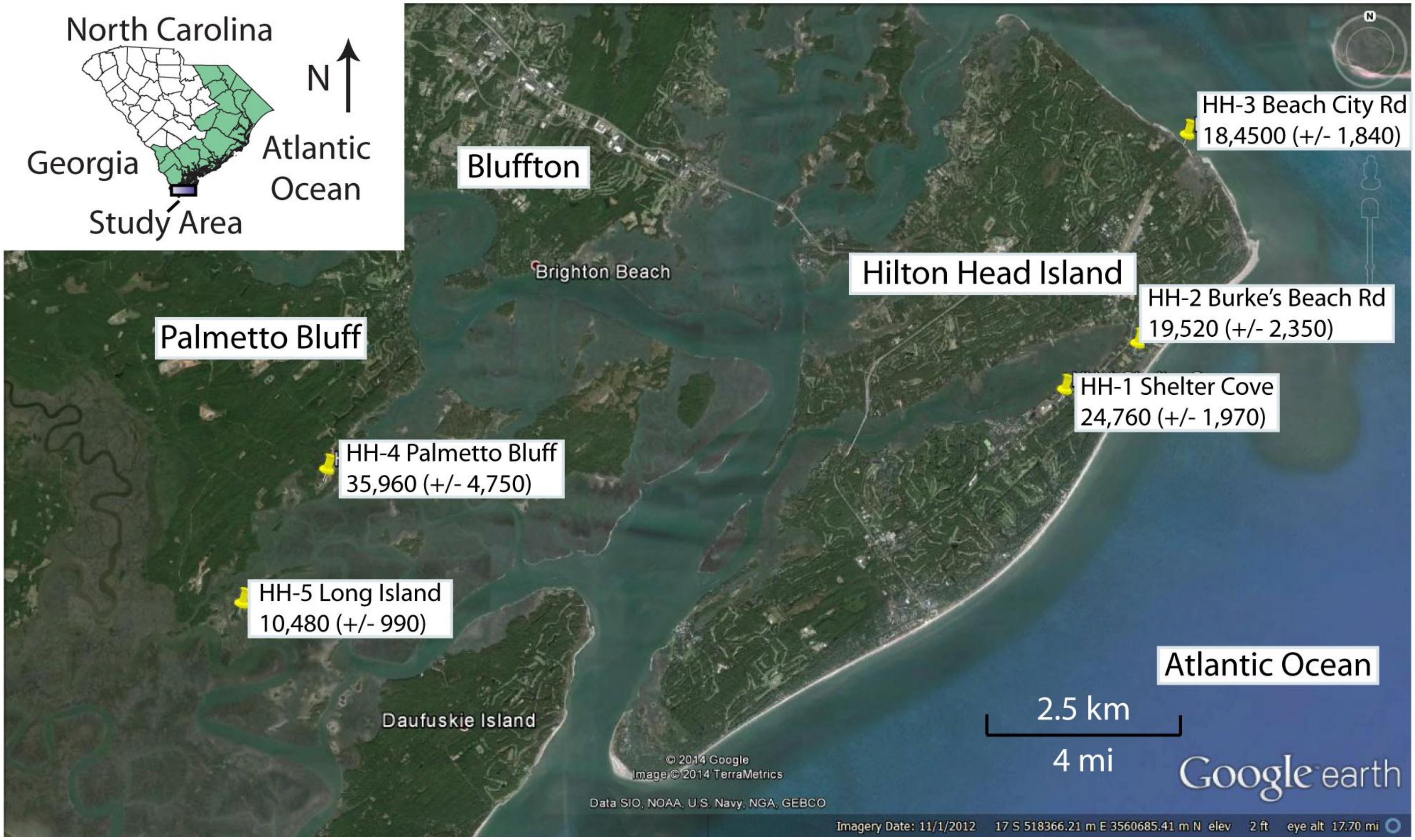


Figure 2.8. Map of Locations and Age Data for Optically Stimulated Luminescence Samples Collected in 2013 from Beaufort County, South Carolina. The data are presented in Table 2.7.

Table 2.7. Optically Stimulated Luminescence Data Collected in 2013 from Beaufort County, South Carolina. Sample locations are presented in Figure 2.8.

Sample ID	UTM WGS Easting	1983 Northing	Elevation meters	Collection depth meters	% Water content[a]	K (%)[b]	U (ppm)[b]	Th (ppm)[b]	Cosmic dose (Gy/ka)[c]	Total Dose Rate (Gy/ka)	Equivalent Dose (Gy)	n[d]	Scatter[e] (%)	Age (yrs)[f]
HH-1	526148	3560693	4	1.2	3 (34)	0.22 ± 0.02	2.58 ± 0.14	10.8 ± 0.31	0.18 ± 0.02	1.47 ± 0.04	34.6 ± 2.63	12 (20)	51.9	24,760 ± 1,970
HH-2	528375	3562227	2	1.3	17 (45)	0.48 ± 0.04	0.33 ± 0.10	2.18 ± 0.37	0.18 ± 0.02	0.70 ± 0.08	13.7 ± 0.67	11 (15)	48.2	19,520 ± 2,350
HH-3	529690	3567302	4	1.5	4 (36)	0.34 ± 0.02	0.82 ± 0.05	2.04 ± 0.17	0.17 ± 0.02	0.71 ± 0.04	13.1 ± 1.13	10 (15)	37.9	18,450 ± 1,840
HH-4	509466	3559299	3	1.5	6 (42)	0.08 ± 0.05	0.67 ± 0.17	4.00 ± 0.52	0.17 ± 0.02	0.57 ± 0.08	20.5 ± 1.39	16 (24)	48.1	35, 960 ± 4,750
HH-5	507492	3556079	2	1.1	9 (42)	0.57 ± 0.06	1.82 ± 0.19	5.31 ± 0.50	0.18 ± 0.02	1.23 ± 0.08	13.2 ± 0.90	17 (24)	40.9	10,480 ± 990

[a]Field moisture, with figures in parentheses indicating the complete sample saturation %. Dose rates (and ages) calculated using 75% of saturated moisture (i.e. 34% * .75 = 26%).

[b]Analyses obtained using high-resolution gamma spectrometry (Ge detector).

[c]Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994). See text for details.

[d]Number of replicated equivalent dose (De) estimates used to calculate the equivalent dose. Figures in parentheses indicate total number of measurements included in calculatingthe represented equivalent dose and age using the minimum age model (MAM) for single aliquot regeneration.

[e]Defined as "over-dispersion" of the De values. Obtained by taking the average over the std deviation. Values >35% are considered to be poorly bleached or mixed sediments.

[f]Dose rate and age for fine-grained 250-180 microns quartz. Exponential and linear components used in the fit of equivalent doses >10 Gy; errors to one sigma, ages and errors rounded.

- Data and analysis provided by the US Geological Survey Luminescence Geochronology lab by Shannon Mahan in 2013.

Barrier facies – Sand, well sorted, fine-medium grained.

Estuarine – silty-sandy clay. Thinly bedded silty clays with scattered peat interbedded with sandy clay.

Transgressive facies – Sand, poorly sorted

Fluvial facies – Gravelly sand, poorly sorted, clay matrix supported, subangular to sub-rounded.

Wicomico alloformation

Sediments of the Wicomico alloformation are generally above the elevation of 21.3 m (70 ft) at their seaward margin where overlapped by the Penholoway alloformation at the Dorchester Scarp. At the landward margin, Wicomico sediments generally are below the elevation of 27.4 m (90 ft) where the deposits overlap, overlie, or abut sediments of the Marietta alloformation at the Surry Scarp.

Barrier facies – Sand, light-gray (N7) to dark-gray (N3), moderately well-sorted, subrounded to well-rounded, fine phosphatic quartz sand, with a minor fraction of medium to coarse quartz sand, as well as fine heavy minerals, shell hash, and trace coarse mica. Deposits from roughly linear, sub-parallel ridges. Thickness 1 to 10 meters.

Estuarine facies – Mud and sand, silty clay or a silt matrix-supported, well-sorted, sub- to very-angular, fine quartz sand grading landward into a poorly sorted, subangular to subrounded, clay matrix-supported, fine to very coarse quartz sand, with minor amounts of fine opaque minerals. Thickness is 2 to 3 meters.

Transgressive surface – Gravel, color variable, poorly sorted, subrounded, sandy quartz gravel. Basal gravels fine upward into poorly sorted, sub- to very-angular, fine to very coarse quartz sand with very angular, very fine opaque minerals. Thickness is less than 1 meter.

Penholoway alloformation

Sediments of the Penholoway alloformation at the surface are generally above the elevation of 17.4 m (57 ft) at their seaward margin where overlapped by the Ladson alloformation at the Macbeth Scarp. At the landward margin, Penholoway sediments generally are below the elevation of 21.3 m (70 ft) where the deposits overlap, overlie, or abut sediments of the Wicomico at the Dorchester Scarp.

Barrier Facies – Sand, sediments fine upward to a well-sorted, subrounded, very fine to fine quartz sand, with trace fine micas. The maximum thickness drilled is 10 meters.

Estuarine facies – Clay and fine sand, color is gray to bluish gray, with variable amounts of shells and shell fragments. Thickness is 1 to 8 meters.

Transgressive surface – Gravel, sand, and mud, color variable, well-rounded quartz pebble zone that fines upward to a silt and clay, matrix-supported, often stiffly plastic, very poorly sorted, subangular, very fine to very coarse quartz sand with a few quartz granules. Thickness is less than 1 meter.

Ladson alloformation

Sediments of the Ladson alloformation at the surface are generally above the elevation of 10.7 m (35 ft) at their seaward margin where overlapped by the Ten Mill Hill alloformation at the Bethera Scarp. At the landward margin, Ladson sediments generally are below the elevation of 17.4 m (57 ft) where the deposits overlap, overlie, or abut sediments of the Penholoway at the Macbeth Scarp.

Barrier facies – Sand, poorly sorted quartz sand, the sediments are better sorted and consist of a well-sorted, subrounded, fine to medium quartz sand, with minor very fine opaque minerals, sparse micas, scattered fine garnet, and epidote sand, and well rounded, very coarse blue quartz sand. The maximum thickness drilled is 9 meters.

Estuarine facies - Sand, silt and clay, color variable, stiffly plastic. Thickness is 3 to 10 meters.

Transgressive surface – Sand and gravel, color variable, sub- to well-rounded, quartz pebble gravel that fines upward to a very poorly sorted, subrounded, very fine to very coarse quartz sand. Thickness is less than 1 meter.

Ten Mile Hill alloformation

Sediments of the Ten Mile Hill alloformation are generally above the elevation of 6.7 m (22 ft) at their seaward margin where overlapped by sediments of the Pamlico alloformation at the Suffolk Scarp. At the landward margin, Ten Mile Hill sediments generally are below the elevation of 10.7 m (35 ft) where the deposits overlap, overlie, or abut sediments of the Ladson at the Bethera Scarp.

Barrier facies – Sand, pale greenish yellow (10Y 9 or 8/2) to pale brown (5YR 5/2) to yellowish-orange (10YR 7/6), subrounded to subangular, well-sorted, very fine to fine quartz sand with common fine heavy minerals; brown phosphorite sand, some silt and clay, and very sparse medium mica. Deposits form broad, linear or curvate, subparallel ridges. Thickness 7 to 17 meters.

Estuarine facies- Clay, gray to brown, may contain subangular very-fine to fine sand or fine micas. Thickness 1-4 meters.

Transgressive surface – Gravel and sand, color variable, poorly sorted, subrounded to very angular, fine to very coarse quartz and phosphorite sand, with well-rounded small (< 2.0 cm) quartz and phosphate pebbles and trace amounts of other, very fine heavy minerals. Thickness is less than 1 meter.

<u>Pamlico alloformation</u>

Sediments of the Pamlico alloformation are generally above the elevation of 5.2 m (17 ft) at their seaward margin where overlapped by sediments of the Princess Anne alloformation at the Awendaw Scarp. At their landward margin, Pamlico sediments generally are below the elevation of 6.7 m (22 ft) where the deposits overlap, overlie, or abut sediments of the Ten Mile Hill alloformation at the Suffolk Scarp.

Barrier facies – Sand, light-gray (N7) to dark-gray (N3), moderately well-sorted, subrounded to well-rounded, fine phosphatic quartz sand, with a minor fraction of medium to coarse quartz sand, as well as fine heavy minerals, shell hash, and sparse coarse mica. Deposits form linear, sub-parallel ridges. Thickness 1 to 17 meters.

Estuarine facies – Mud and sand, medium light gray (N6), uniform-textured clay with mica flakes; and well-sorted, subrounded to subangular, fine to very fine quartz sand and sand laminae. Both sediments are typical of low energy, tidal, estuarine deposits. Thickness is 1 to 2 meters.

Transgressive surface – Gravel and sand, color variable, poorly sorted, subrounded to very angular, fine to very coarse quartz and phosphorite sand, with well-rounded small (< 2.0 cm) quartz pebbles and trace amounts of other, very fine heavy minerals. Thickness is less than 1 meter.

Princess Anne alloformation

Sediments of the Princess Anne alloformation are generally above the elevation of 3 m (10 ft) at their seaward margin where overlapped by the Silver Bluff alloformation at the Mt. Pleasant Scarp. At the landward margin, Princess Anne sediments generally are below the elevation of 5.2 m (17 ft) where the deposits overlap, overlie, or abut sediments of the Pamlico alloformation at the Awendaw Scarp.

Barrier Facies – Sand, light-gray (N7) to dark-gray (N3), phosphatic, poorly to moderately well-sorted, subrounded to well-rounded, fine quartz sand with abundant fine heavy minerals, medium shell sand, shell hash, and trace amounts of fine mica. Deposits form linear to curvate, subparallel ridges. Thickness 1 to 17 meters.

Estuarine facies – Mud and sand, medium light gray (N6) to medium bluish gray (5B 5/1) and is a muddy sand to sandy mud, clay, silt, silty sand, clayey sand, phosphorite sand and quartz sand and shells. Some zones contain both broken and intact *Oliva, Polinices*, *Terebra, Mercenaria* and *Dosinia* shells. Thickness is less than 3 meters.

Transgressive surface – Sand, medium bluish-gray (5B 5/1), poorly sorted, subrounded to very angular, fine to very coarse quartz and phosphorite sand, with trace amounts of other, very fine heavy minerals. Thickness is less than 1 meter.

Foreshore facies – Sand, medium-gray (N5), angular to well-rounded, well-sorted, fine to medium quartz and shell sand with minor fine fraction of heavy minerals and shell fragments. The shells (*Mulinea and Mercenaria campechiensis*) rarely compose more than 30 percent of sediment. These quartz and shell sand are typically deposited in the lower part of the swash zone and in the shallow wave base. Thickness is 1 to 3 meters.

Silver Bluff alloformation

Sediments of the Silver Bluff alloformation at the surface are generally above the elevation of 2 m (6 ft) at their seaward margin where overlapped by Holocene deposits. At their landward margin, Silver Bluff sediments generally are below the elevation of 3 m (10 ft), where the deposits overlap, overlie, or abut sediments of the Princess Anne alloformation at the Mt Pleasant Scarp.

Barrier facies – Sand, light-gray (N7) to dark-gray (N3), poorly to moderately well-sorted, subrounded to well-rounded, fine quartz sand with a minor fraction of fine heavy minerals, phosphorite sand, and shell hash. Deposits form linear, subparallel ridges that are commonly welded to older terrace or barrier deposits. Thickness 1 to 17 meters.

Estuarine facies – Mud, medium bluish-gray (5B 5/1) to greenish-gray (5G 6/1), poorly to very well-sorted, subangular to subrounded, very fine to fine clayey quartz sand to sandy clay with minor, very fine heavy minerals. Where silt and clay occur, the sediment typically is soft. Often thin, younger deposits infill topographic lows in older estuarine deposits. Thickness is 2 to 10 meters.

Transgressive surface – Gravel and sand, mud, color variable, poorly sorted, subrounded to very angular, fine to very coarse quartz and phosphorite sand, with well-rounded small (< 2.0 cm) quartz pebbles and trace amounts of other, very fine heavy minerals. Thickness is less than 1 meter.

Waiter Island alloformation

Deposits of the Waiter Island alloformation are the result of a possible earlier Holocene highstand and consists of fine to medium quartz sand with minor amounts of heavy minerals.

CONCLUSIONS

The Transgressive Surface of Erosion is the most useful surface for formation delineation. The Maximum Flooding Surface, where preserved, is the second-most useful surface. The identification of the transgressive lag or back barrier estuarine sediments related to the Transgressive Surface of Erosion is critical to understanding the stratigraphic relationships in the Middle and Lower Coastal Plains. Once this identification is completed, an easily identifiable map-scale record of Pleistocene transgressions exists.

One named Pliocene and eight named Pleistocene erosional marine scarps are related to sea-level highstands that created South Carolina’s surficial deposits. Pleistocene marine sediments first identified by their geomorphic properties as terraces, with the additional geological data, can be identified and defined as separate alloformations. The internal sediments are genetically related transgression and highstand deposits, separated from other deposits by unconformities, with scarps and terraces as part of the diagnostic boundaries. Continuing to use the scarp and terrace nomenclature is an important part of the identification of the formations and their stratigraphic position but acknowledging the units as alloformations completes the conceptual picture.

One scarp is formally proposed here (Macbeth), two are revised (Dorchester, Bethera), and four are abandoned (*Mechanicsville, Summerville, Cordesville, Cainhoy*).

With the downward revision of the Pliocene-Pleistocene boundary, one marine Pliocene terrace and formation and eight Pleistocene alloformations at the surface are recognized in South Carolina (Table 2.6). The *Bear Bluff Formation* is abandoned; its lower part is referred to the Goose Creek Limestone and its unconformably overlying upper part is referred to the Marietta alloformation. The *Talbot* is abandoned as it has been shown to be composed of separate alloformations with separate overlying terraces. The *Canepatch* and *Socastee* formations are abandoned: they cross established transgressive time-lines and are in conflict with the published ages of the alloformations.

ACKNOWLEDGEMENTS

We thank the South Carolina Geological Survey and the United States geological Survey’s National Cooperative Mapping Program (STATEMAP) for providing support and funding for the mapping that provided the data presented within. We also thank all of the previous workers for their efforts and geological products that allowed us to not start from scratch with this project. We could not have produced this without their work. We also thank Robert E. Weems and Christopher G. St. C. Kendall for their help with and earlier draft of this manuscript.

CHAPTER 3

An analysis and comparison of observed Pleistocene South Carolina (USA) shoreline elevations with predicted elevations derived from Marine Oxygen Isotope Stages (MIS).[2]

[2]Doar, W. R., III, and C. G. St. C. Kendall. 2014. *Quaternary Research*, v. 82, n. 1, p. 164-174. Reprinted here with permission of publisher- Appendix B

ABSTRACT

Geological maps of South Carolina, covering >6,800 km^2, confirm the existence of eight preserved Pleistocene shorelines above current sea level: Marietta (+42.6 m), Wicomico (+27.4 m), Penholoway (+21.3 m), Ladson (+17.4 m), Ten Mile Hill (+10.7 m), Pamlico (+6.7 m), Princess Anne (+5.2 m), and Silver Bluff (+3m). Current geochronologic data suggest these 8 shorelines correlate with Marine Oxygen Isotope Stages (MIS) as follows: Marietta-older than MIS 77; Wicomico-MIS 55-45; Penholoway-MIS 19 or 17; Ladson-MIS 11; Ten Mile Hill-MIS 7; Pamlico-MIS 5; Princess Anne-MIS 5; and Silver Bluff-MIS 5 or 3. Except for the MIS 5e Pamlico, and possibly the MIS 11 Ladson, the South Carolina elevations are higher than predicted by isotope proxy-based reconstructions. The less than 4 m of total relief from the Pamlico to the Silver Bluff shoreline in South Carolina, while other reconstructions suggest an expected relief of approximately 80 m, illustrates the lack of match. Our results suggest that processes affecting either post-depositional changes in shoreline elevations or the creation of proxy sea-level estimates must be considered before using paleo sea level position on continental margins.

INTRODUCTION

South Carolina's (SC) Pleistocene marine coastal plain deposits are well developed and problematic. Lithostratigraphic-based mapping of South Carolina shows relative sea level (RSL) highstand elevations for the last 2 Ma ranging from 42.6 to 3 m above present sea level. However, analysis of the complex processes acting on these shorelines shows they do not entirely fit predicted sea-level histories derived from studies far afield. For example, only 8 Pleistocene highstand-related formations are preserved at the surface in SC. This is much smaller than the number of marine isotope stage (MIS) highstands (odd number stages) for the Pleistocene. This misfit between the observed predicted global sea-level highstands indicates the complexity of determining past sea-level elevations. Correlating our work to other locations along the southeast United States (SE US) coast provides a regional-scale perspective of the land-based records as one record of the worldwide Pleistocene sea-level history.

BACKGROUND

The Evolving Concepts of Shoreline Studies in South Carolina

Our study area lies on the eastern coast of North America south of where G. B. Shattuck (1906) published the first stratigraphic maps of Maryland’s eastern shore. He introduced the concept of escarpments (scarps) and terraces as markers for former sea-level positions (Table 3.1) following G. K. Gilbert’s (1890) description of similar features of former Lake Bonneville, Utah. These scarps represent the inland limit of their associated marginal marine sedimentary terraces, and their packages of associated sediments were called formations (Shattuck, 1906; 1907). Later C. W. Cooke (1930 b; 1936) correlated coastal terraces and produced paleoshoreline maps for the Coastal Plain of South Carolina (SC). D. J. Colquhoun (1965; 1969 a; 1969 b; 1974) added boreholes to depict the subsurface lithostratigraphy. R. E. Weems with many other workers (Table 3.1) continued Cooke’s and Colquhoun’s

Table 3.1 Significant Pleistocene stratigraphic publications on the Southern Atlantic Coastal Plain that have influenced the lithostratigraphic concepts and stratigraphy of the Pleistocene section of South Carolina by author with a brief summary of each publication's major point.

Publication	**Subject**
Tuomey, 1848	Geology of South Carolina
Dall and Harris, 1892	Review of stratigraphy
Shattuck, 1901 a & b	Established marine scarp and terrace concept and Wicomico and Talbot Formations in Maryland
Stephenson-	Pleistocene marine stratigraphy of NC; established
In Clark et al., 1912	many formations
Cooke, 1936	Map of SC coastal plain paleo-shorelines
Flint, 1940	Compiled stratigraphy
Richards, 1950	Updated NC stratigraphy
Malde, 1959	Proposed Ladson Formation
Colquhoun, 1965, 1974; Colquhoun et al., 1991	Expanded and refined Cooke, 1936 shorelines and formations
DuBar et al., 1974	Mapped NE corner of SC coastal plain
Healy, 1975	Mapped terraces in Florida
Newton et al., 1978	Age of the Waccamaw Formation
Wehmiller and Belknap, 1982	Geochronology
McCartan et al., 1984	Geological map and ages of SC Middle and Lower Coastal Plain deposits
Weems and Lemon, 1984 a & b;	Geological Maps of parts of Charleston County, SC
1985; 1989; 1993	
Weems, Lemon, and Cron, 1985	Age dates and map of Charleston, SC area
Weems, Lemon, and McCartan, 1985	Geological Map of Charleston, SC area
Weems et al., 1987 a, b	Geological Maps of parts of Charleston County, SC
Johnson and Berquist, 1989	Revised Virginia coastal plain stratigraphy
Weems, Lemon, and Nelson, 1997	Geological Map of part of Charleston County, SC
Harris, 2000	Geological Map and age dates of Edisto Island and Adams Run, SC area
Weems and Lewis, 1997; 2002	Geological Maps of parts of Charleston County, SC

morphostratigraphic scheme while mapping the central portion of SC's Lower Coastal Plain. W. R. Doar and R. H. Willoughby (Figure 3.1; Tables 3.1, 3.2, 3.3, and 3.4) have expanded the spatial coverage of earlier workers. A comprehensive list of authors and publications contributing to the presently known stratigraphy is presented in Table 3.2.

Our maps show established geologic and geomorphic features, including formations, paleoshorelines, escarpments, and terraces (for terms and definitions see Table 3.4). In SC, various authors mapping scarps and terraces assigned names based on geographic names. Other authors assigned names to the distinct mappable packages of genetically related sediments (Formations). The modern conventions for naming formations (e.g. the North American Code of Stratigraphic Nomenclature, 2005) result in formations and their associated overlying terraces (produced from the same transgression) not always having the same name. To avoid confusion here, we chose to refer to the Formation names throughout this paper for each related transgression.

Relationships of Sediments to Morphology

The coast of SC is typically a sediment-starved system (Gayes et al., 2002; Gayes et al., 2003; Ojeda et al., 2004). In such systems, transgressions create accommodation through shoreline erosion (*sensu strictu* Jervey, 1988). Transgression is followed by deposition of the eroded sediment into the newly created space, as opposed to infilling with surplus imported sediments. This results in a 1 to 2° seaward incline on the plain (Cronin et al., 1981) creating a physiographical flat terrace (Figure 3.2). Each subsequent transgression, that does not overtop existing deposits, repeats the process at slightly lower elevations. This produces distinct mappable packages of genetically related sediments,

Table 3.2- Southeastern North America’s Pleistocene formations and their scarp toe elevations.

Publication	Formation	Scarp	Toe Elevation
Colquhoun	Silver Bluff	*	+3 m (+10)
(1974)	Princess Anne	Awendaw	+4.6 m (+15)
	Pamlico	Suffolk	+7.6 m (+25)
	Talbot	Bethera	+12.2 m (+40)
	Penholoway	Summerville	+21.3 m (+70)
	Wicomico	Dorchester	+33.5 m (+110)
	Okefenokee	Parlor	+41 m (+135)
Hoyt and Hails	Silver Bluff	*	+1.4 m (+4.5)
(1974)	Princess Anne	*	+4 m (+13)
	Pamlico	*	+7.3 m (+24)
	Talbot	*	+12.2-13.7 m (+40-45)
	Penholoway	*	+21.3-22.8 m (+70-75)
	Wicomico	*	+28.9-30.4 m (+95-100)
Weems	Silver Bluff	Mt Pleasant	+3 m (+10)
(from various maps)	Wando	Awendaw/ Suffolk	+5.2 m (+17)
	Ten Mile Hill	Bethera	+10.7 m (+35)
	Ladson	*	+17.4 m (+57)
	Penholoway	Summerville	+21.3-22.8 m (+70-75)
	Wicomico	Dorchester	+27.4-28.9 m (+90-95)
Doar and Willoughby	Silver Bluff	Mt Pleasant	+3 m (+10)
(2006)	Princess Anne	Awendaw	+5.2 m (+17)
	Pamlico	Suffolk	+6.7 m (+22)
	Ten Mile Hill	Bethera	+10.7 m (+35)
	Ladson	Macbeth	+17.4 m (+57)
	Penholoway	Summerville	+21.3-22.8 m (+70-75)
	Wicomico	Dorchester	+27.4-28.9 m (+90-95)
Doar and Berquist	Silver Bluff/Tabb- Poquoson mbr		+3 m/ 2.2 m (+9.8 ft/ 7.2 ft)
(2009) SC/VA	Princess Anne/Tabb- Lynnhaven mbr		+5.2 m/ 5.5 m (+17 ft/ 18 ft)
	Pamlico/Tabb- Sedgefield		+6.7 m/ 8.5 m (+22 ft/2 8 ft)
	Ten Mile Hill		+10.7 m (+35 ft)

	Shirley		+14.6 m (+48 ft)
	Ladson/Chuckatuck		+17.4 m/ 17.4 m (+57 ft)
	Penholoway/Charles City		+21.4 m/ 23.1 m (+70 ft/ 76 ft)
	Wicomico/Windsor		+27.5 m/ 28.9 m (+90 ft/ 95 ft)
Doar and Kendall (2014)	Silver Bluff	Mt Pleasant	+3 m (+10)
	Princess Anne	Awendaw	+5.2 m (+17)
	Pamlico	Suffolk	+6.7 m (+22)
	Ten Mile Hill	Bethera	+10.7 m (+35)
	Ladson	Macbeth	+17.4 m (+57)
	Penholoway	Summerville	+21.3-22.8 m (+70-75)
	Wicomico	Dorchester	+27.4-28.9 m (+90-95)
	Marietta	Parler	+42.3 (+145)

- indicates scarps not named

Table 3.3- A list of 52 7.5 Minute Geological Quadrangle maps of the Pleistocene by William R. Doar, III. The maps are based on the USGS 7.5-minute topographic maps. The stratigraphy discussed in this paper when comparing observed to predicted sea levels is supported by these maps and their associated boreholes and cross sections. All maps and boreholes are on file at the South Carolina Geological Survey. www.dnr.sc.gov/geology/

Allendale *	Fripps Inlet (2000)	Pritchardville (2002 a)
Alvin*	Frogmore (2000, 2003 h)	Ridgeland*
Barton*	Ft Pulaski (2002 e)	Rincon (2004 b)
Beaufort (2003 f)	Georgetown South*	Rockville*
Bennett's Point (2003 c)	Gifford*	St. Helena Sound (1999, 2003 g)
Briar Creek Landing*	Greeleyville*	St. Phillips Island (2000)
Bull Pond*	Hardeeville (2004 b)	St. Stephens*
Bluffton (2001 b)	Hardeeville, NW (Schultz et al., 2011)	Sandridge*
Bonneau*	Hilton Head Island (2002 b)	Savannah (2002 c)
Cedar Creek*	Holly Hill*	Solomons Crossroads*
Chicora*	Jamestown*	Spring Island (2001 d)
Cordesville*	Jasper (2001 a)	Summerville, NW*
Cross*	Kilsock Bay*	Tillman*
Dale (2003 a)	Laurel Bay*	Tybee Island North (2002 d)
Eadytown*	Limehouse (2004 a)	Wiggins (2003 b)
Edisto Beach (1999, 2003 e)	Moncks Corner*	Vance*
Edisto Island (1999, 2003 d)	Parris Island (2000, 2001 c)	
Eutawville*	Port Wentworth (2004 a)	

*Geologic Quadrangle Maps In-press, on file at the South Carolina Geological Survey.

Table 3.4- Definitions of terms and their specific use in text.

Scarp
A scarp is "a relatively steep sloping surface that generally faces in one direction and separates level or gently sloping surfaces" (Neuendorf et al., 2005, p. 577). In the context of this paper scarps are erosional.
Scarp toe
The "toe" of a scarp is the point (elevation) where the surface of younger sediments touches, abuts, or overlies, an older, higher elevation, sediment surface; or, the surface expression of the unconformity that separates two deposits of differing ages.
Terrace
A terrace is defined as "a narrow, gently sloping, coastal platform veneered by sedimentary deposits and bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope" (Neuendorf et al., 2005, p. 663).
Formation
A Formation is defined by the North America Commission on Stratigraphic Nomenclature (2005) as "a body of rock identified by lithic characteristics and stratigraphic position; it is prevailingly but not necessarily tabular, and is mappable at the Earth's surface or traceable in the subsurface". The formations of South Carolina's Coastal Plain are commonly tabular, mappable bodies of sediment that are identified by lithic characteristics, unconformable surfaces, and stratigraphic position.
Unconformity
The sequence stratigraphic concept of an unconformity is used. An unconformity is " a surface separating younger from older strata along which there is evidence of subaerial-erosion truncation and, in some areas, correlative submarine erosion, a basinward shift in facies, onlap, truncation, or abnormal subaerial exposure, with a significant hiatus indicated" (Neuendorf et al., 2005, p. 695).

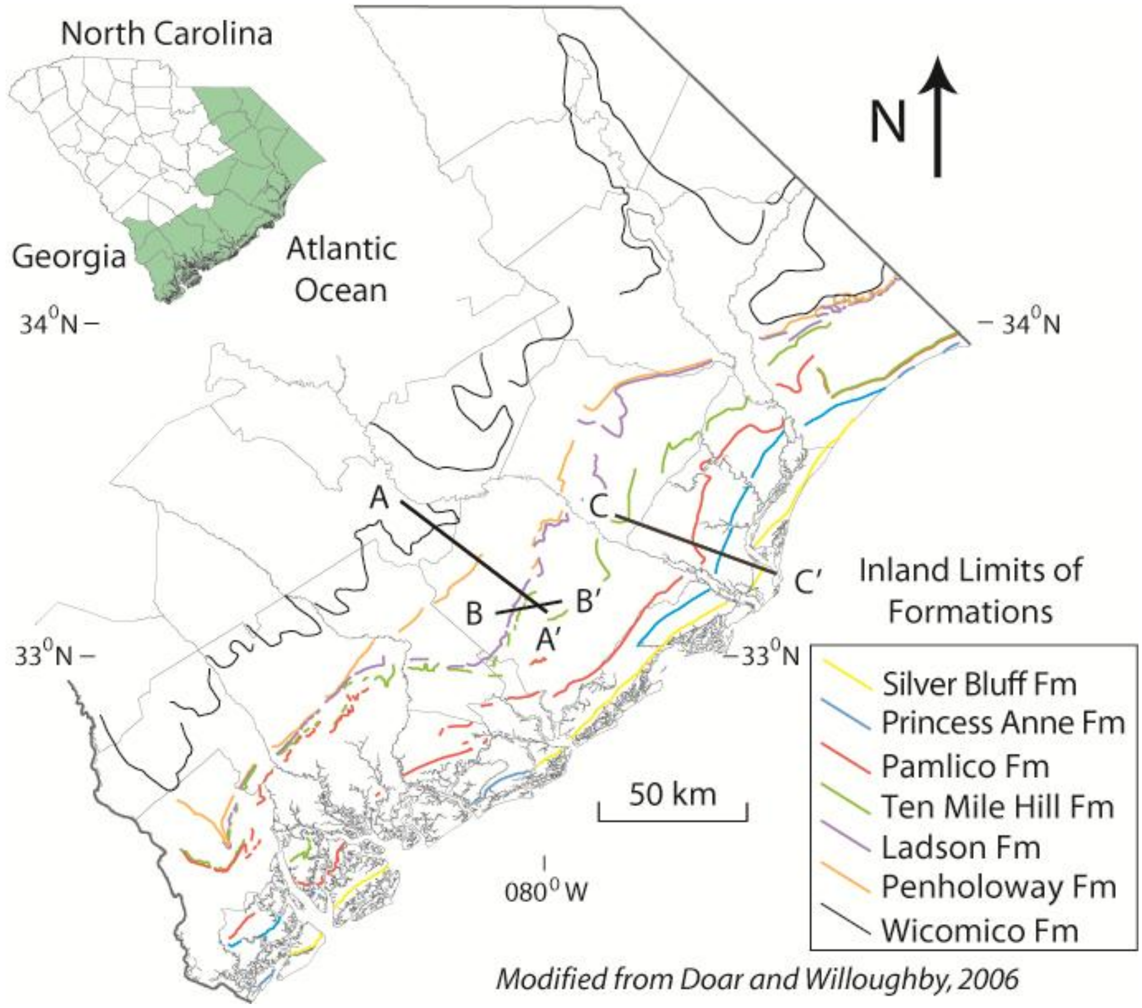


Figure 3.1- Generalized map of the Pleistocene scarps. The scarps separate the Pleistocene formations at the surface and are used to determine shoreline elevations. More information on individual formations is found in Table 1 and generalized map of the Pleistocene marine deposits (based on 1:24,000-scale geological mapping and physiography) and cross-sections A, B, and C are included in the Figure 3.8.

separated by erosional scarps at the surface, overlying each new unconformity (Figure 3.2 and 3.3). Erosional scarps therefore define the inland contact of younger sediments against older sediments and are the surficial expressions of unconformities.

Geologic Setting

Following the opening of the Atlantic Ocean, about 180 Ma (Manspeizer et al., 1978), the Atlantic coast of North America, including SC, became a trailing edge margin. Heller et al. (1982) stated that by the Pliocene and Pleistocene, thermal subsidence related to the Atlantic spreading center had slowed and presently the coastal plain of SC is composed of a southeastward-dipping wedge of calcareous and siliciclastic sediment (Poag, 1985). The Marietta unit (informal), located in the Middle Coastal Plain (DuBar et al., 1974), and its associated Parler scarp (Colquhoun, 1974), mark the inland limit of Pleistocene highstand deposits.

METHODS

There are very few exposures of the strata beneath the Coastal Plain surface. The authors have relied heavily on geomorphological assessments and subsurface borings to determine the stratigraphy. About 1,500 boreholes were used to produce 52 7.5 minute, 1:24,000-scale geological quadrangle maps covering >6,800 km^2 (Table 3.4; all maps and logs on file at the South Carolina Geological Survey). Surface elevations were determined from 1:24,000-scale USGS topographic maps [usually 5 ft (~1.5 m) contour interval] with an elevation error of one contour interval. Boreholes were drilled using a modified well-drilling truck fitted with 11.43 cm diameter, 1.52 m long solid-stem

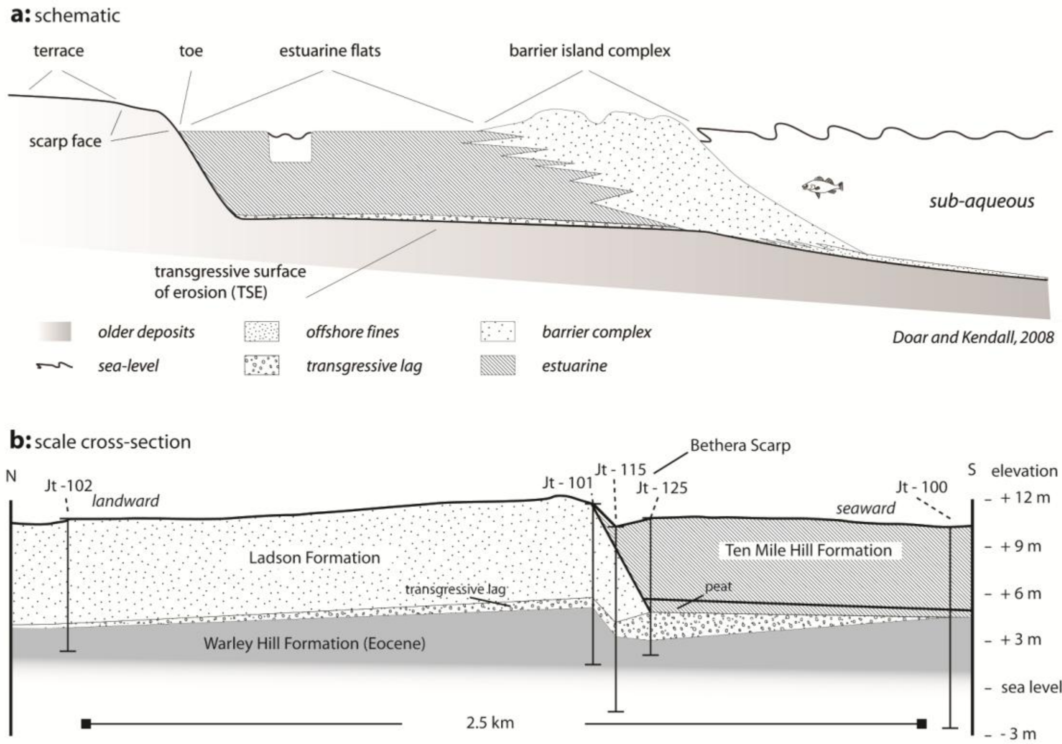


Figure 3.2- Relationship of topography, facies changes and reconstructed sea level. a) Schematic cross-section of a highstand deposit. This geometry results from a sediment-starved system eroding older sediments while cutting accommodation space during the transgression and filling that space with recycled and new sediments. As shown, the scarp toe is a marker for maximum sea-level position. b) Cross-section through the Bethera Scarp near Jamestown, South Carolina with the borehole control. This detailed section illustrates the general principles in a) by showing the overlapping geometry of the younger Ten Mile Hill Formation (seaward) over the older Ladson Formation (landward). The Bethera Scarp separates the formations at the surface.

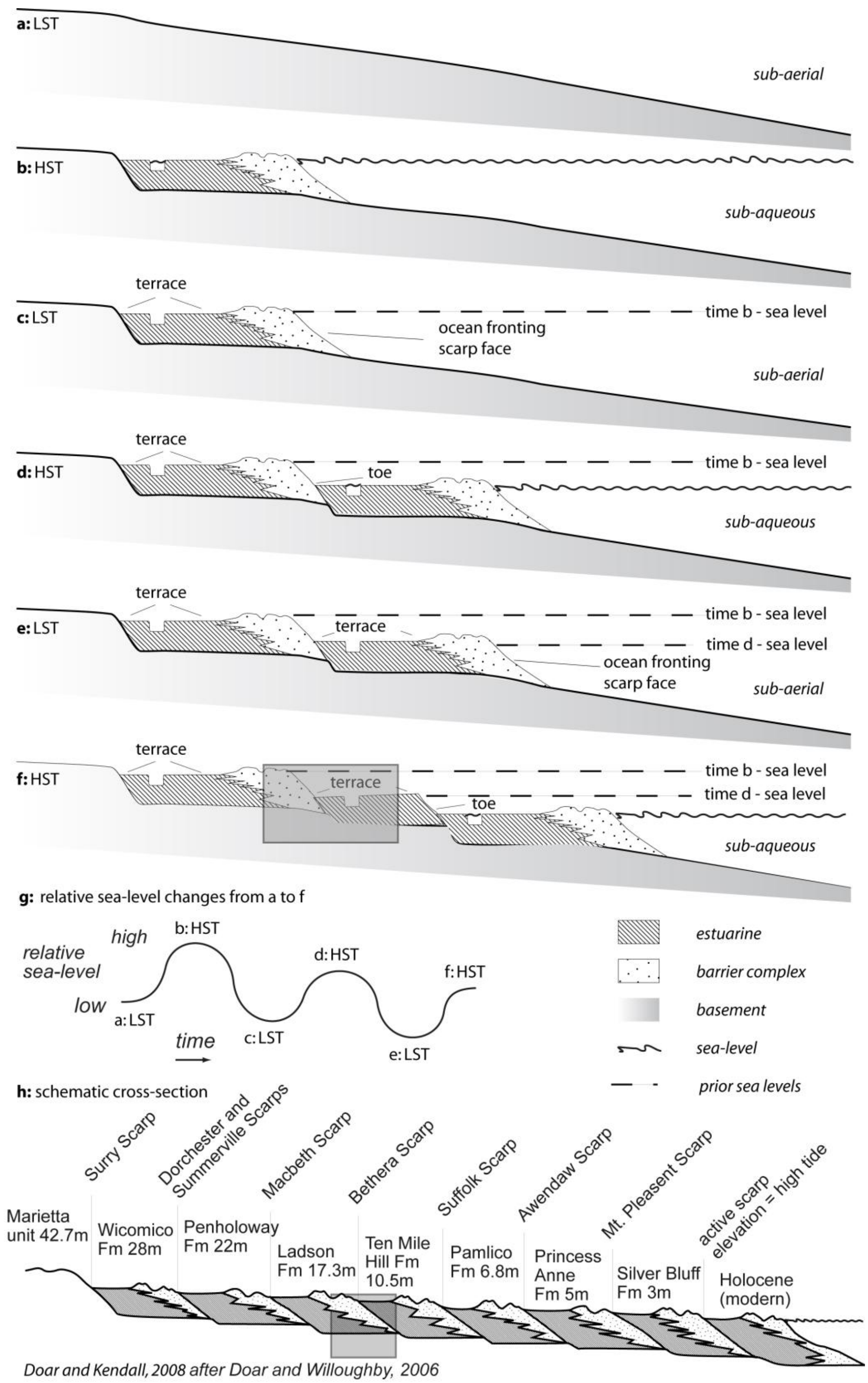

a: LST
sub-aerial
b: HST
sub-aqueous
terrace
c: LST
time b - sea level
ocean fronting scarp face
sub-aerial
terrace
d: HST
time b - sea level
toe
sub-aqueous
terrace
e: LST
time b - sea level
terrace
time d - sea level
ocean fronting scarp face
sub-aerial
terrace
f: HST
terrace
time b - sea level
time d - sea level
toe
sub-aqueous
g: relative sea-level changes from a to f
relative sea-level
high
low
a: LST
b: HST
c: LST
d: HST
e: LST
f: HST
time
estuarine
barrier complex
basement
sea-level
prior sea levels
h: schematic cross-section
Surry Scarp
Dorchester and Summerville Scarps
Macbeth Scarp
Bethera Scarp
Suffolk Scarp
Awendaw Scarp
Mt. Pleasent Scarp
active scarp elevation = high tide
Marietta unit 42.7m
Wicomico Fm 28m
Penholoway Fm 22m
Ladson Fm 17.3m
Ten Mile Hill Fm 10.5m
Pamlico Fm 6.8m
Princess Anne Fm 5m
Silver Bluff Fm 3m
Holocene (modern)
Doar and Kendall, 2008 after Doar and Willoughby, 2006

Figure 3.3 a-f) Down-stepping highstand model for multiple sea-level highstands noting the system tracts. HST is Highstand System Tract. LST is Lowstand System Tract. a, c, and e) LST's. b, d, and f) HST's. In this model, each preserved highstand's transgression did not overtop, or completely remove, older highstand deposits. g) Relative sea-level curve for diagrams a-f. h) Summary schematic cross-section for the Pleistocene marine deposits in South Carolina with the formations and associated scarps. A detailed version of this cross-section is included in Figure 3.8b. The elevations noted are the mapped elevations for scarp toes. The full extent of the Marietta unit has not been mapped therefore the inland extent (Parler scarp at + 42.6 m) is not shown. The gray-shaded boxes highlight the position of the cross-sections in Figure 3.2.

continuous-flight auger rods. The holes depths are as shallow as 3 m and as deep as 43 m with an average of 15 m. The borings have an average grid-spacing of 3 km. This spacing was modified where needed to verify the presence of scarps and their toes or the discovery of complex subsurface geology. The auger rods were drilled vertically into the ground for 3 meters. To minimize disturbance of the sediments, augers were rotated ~1 rotation per auger flight. The auger rods were hoisted to the surface with the sediment trapped between the auger flights. The sediments were examined in the field with a 10x loupe magnifier and their position and physical characteristics were logged (e.g. surface elevation, depth, grain size, composition, sorting, rounding, color, induration).

These sediment descriptions were used to interpret the facies associations and the geometry of genetically-related sediments. Examples of interpretive facies packages from inland to shoreline are: moderate brown (Munsell color 5*YR* 4/4), woody peat with clay is interpreted as swamp or freshwater marsh deposits; medium bluish-gray (Munsell color 5*B* 5/1), clays with sand, silt, or oyster shells and other shell fragments are interpreted as estuarine deposits; variously colored, poorly to very poorly sorted, quartz sands and shell hashes are interpreted as estuarine channel lag deposits; very well- to well-sorted, light- to medium-gray or medium bluish-gray (Munsell colors *N*8-*N*5 or 5*B* 5/1), fine-grained, subrounded quartz sands with 1-2 mm thick zones of heavy minerals are interpreted as beach-face deposits. The method of sample collection means that the bedding and fine bedding structures orientations typically were not preserved. Ideally the transgressive facies noted above should be stacked above each other, with the inland-most facies at the bottom and each subsequent facies stacked above it. However, in many areas the facies were found laterally adjacent to one another (Figure 3.2 and 3.3).

In this sediment-starved system, sediments from older deposits are often recycled through erosion, removing paleosols that might identify unconformable surfaces and producing sediments from the same facies in different formations. Therefore, identifying unconformities is crucial to identifying formations. Unconformities between formations were identified by grain size change, facies interpretation, stacking patterns, a transgressive lag or estuarine facies above an erosional surface (Figure 3.2), and elevation only after multiple holes (> 5) were drilled through a terrace from scarp to scarp. Once the formations were mapped, depositional and stratigraphic models were created (Figure 3.4) and the scarp toe elevations were determined. These toe elevations were used to infer the maximum elevation of a marine highstand to within one meter (Doar and Willoughby, 2006; Doar and Kendall, 2008; Doar and Berquist, 2009) (Figure 3.2a; Table 3.2). The barrier island facies were not used as indicators of former RSL elevation due to significant variations (up to10 m) in barrier crest elevation above the related sea level.

Due to the sediment composition the chronologic data (absolute ages) are limited. Pleistocene age of these deposits precludes the use of biostratigraphic markers because many species are extant. The employed geochronology control is reported in Table 3.5. A comprehensive stratigraphic model (Figure 3.3g) is the result of the relative age data integrated with the existing geochronology. This stratigraphic model hence can be compared with other estimates of sea-level once local processes that might have modified the original elevation are considered. The processes considered follow.

We examined tectonic uplift reported for the area. Dowsett and Cronin (1990) calculated the tectonic uplift rate for the Orangeburg Scarp, the inland limit of Pliocene deposits in SC, as 0.02 $x10^{-1}$ mm/yr to 0.05 x 10^{-1} mm/yr based on data from Soller's (1988) work in the Cape Fear River Valley. We assume that regional rate has been constant since the generation of the scarp and only localized uplift could have affected the shorelines. Using this rate, and the chronological ages provided in Table 3.5, we calculated the probable tectonic uplift of each formation.

Next, glacio-isostatic and hydro-isostatic adjustments (GIA and HIA respectively) to the coast are processes that flex the crust by changes in ice or water loads. The GIA values in the study area have been extracted from existing publications (for list see Table 3.6).

To quantify how transgressions and regressions induce HIA, we explored hydro-isostatic flexure of the crust under various conditions using a 2D instantaneous response model (OSXFlex2D software; Cardozo, 2013) using formulas and algorithms from Hetenyi (1946) and Bodine (1981). In essence the rate and magnitude of crustal deflection was determined by the mass of the added water column, the crust thickness, and mantle density. The change in water depths (bathymetry) over the continental slope for each formation, from highstand to lowstand, were based on our mapped shoreline elevations combined with water depths assumed to be similar to modern bathymetric depths from NOAA coastal charts. The elastic thickness of the crust was 60 km based on VM5a in Peltier and Drummond (2008). The mantle density used was 3,300 kg/m^3. The distances used (km) were measured from the preserved shorelines to the present continental shelf edge. (See details in Supplemental Material section.)

Table 3.5- Geochronology of Pleistocene Marine Formations of South Carolina. The geochronology used in this paper is based on various studies summarized by formation.

	Geochronology of the Pleistocene Marine Formations of South Carolina							
Formation	**Scarp**	**Scarp Toe Elevation (m)**	**Assigned age**	**Numerical technique**	**Error range**	**Stratigraphic context**	**Reference**	**Notes**
Marietta unit	Parler	42.6	1.8-2.4 Ma, 2.3 Ma+, 1.6 Ma	Rubidium/Strontium, Planktonic Forams Zone PL5		Correlation with Bear Bluff Formation	McCartan et al., 1982; Markewich et al., 1992; Weems et al., 2011	Correlated with upper part of the Bear Bluff Fm, basal shell lag in NC
Wicomico	Surry	27.4 – 28.9	1.80-2.12 Ma, 1.4-1.6 Ma	Strontium 87/86	(± 150 ky)	Macrofossils	Weems et al., 1997; McGregor, 2011	Older age correlated with Bear Bluff Fm
Penholoway	Dorchester	21.3 – 22.8	730 - 970 ka	Uranium disequilibrium series	10%	Corals	Weems and Lemon, 1989	
Ladson	Macbeth	17.4	400 or 450 ka	Uranium disequilibrium series	10%	Corals	McCartan et al., 1984; Weems and Lemon, 1989	
Ten Mile Hill	Bethera	10.7	200 - 240 ka	Uranium disequilibrium series, Paleontology, Optically stimulated luminescence	10%, range of fossil species overlap, as little as 5%	Corals, Fossils from SC, Sands	Szabo, 1985; Weems et al., 1997; Sanders et al., 2009; Willis, 2006	Referred to as Talbot Formation or terrace in older publications
Pamlico	Suffolk	6.7	90 - 120 ka	Uranium disequilibrium series	10%	Corals	Wehmiller and Belknap, 1982	Younger dates may be the Princess Anne Fm
Princess Anne	Awendaw	5.2	80 - 100 ka	Uranium disequilibrium series, Amino acid racemization, Optically stimulated luminescence	10%, Based on absolute age determinate, as little as 5%	Corals in beach swash zone, Amino acid racemization on bivalves, Quartz sand in beach ridges	York et al., 2001; Wehmiller et al., 2004; Willis, 2006	Two groups of dates- Optically stimulated luminescence - 78-90 ka and 100 ka, Amino acid racemization and U/Th - 80 ka
Silver Bluff	Mt. Pleasant	3.0	34 ka, 35 ka, 100 ka	Carbon 14, Carbon 14, Optically stimulated luminescence	As little as 5%, ± 1830	Peat deposits, Quartz sand in beach ridges	Hoyt and Hails, 1974; Weems and Lemon, 1993; Zayac, 2003	Formation mapped between Princess Anne Fm and Modern deposits

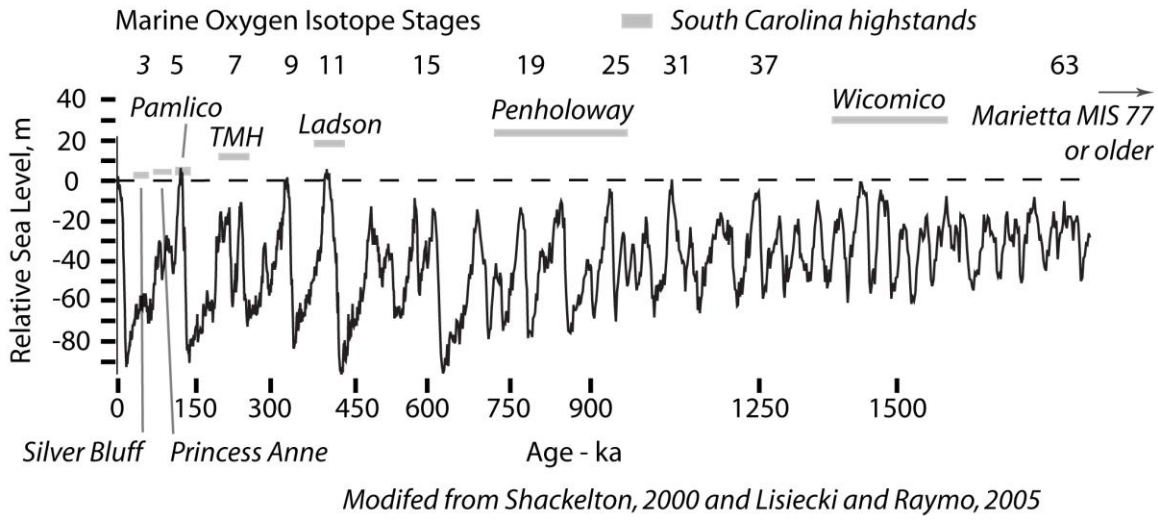


Figure 3.4- Isotope based sea-level reconstruction curve after Shackleton (2000) and Lisiecki and Raymo (2005) with the South Carolina shoreline elevations. The gray rectangles represent the maximum elevation and age range for each Pleistocene formation along the Atlantic Coastal Plain (Table 3.2). The offset between the rectangles and the MIS-based sea-level positions is the major issue discussed in the text

Table 3.6- Significant publications, by author, related to shoreline elevations derived from Marine Isotope studies that have influenced the predicted paleo-sea level concepts and stratigraphy of the Pleistocene section of South Carolina, with a brief summary of each publication's major point.

Publication	Study Subject	Study Focus	Study Location
Bard et al., 1990	Coral Studies	U/Th ages	Barbados
Bender et al., 1979	Coral Studies	U/Th ages	Barbados
Chappell, 1974	Coral Studies	Coral Reef Shorelines	Huon Peninsula, New Guinea
Cronin et al., 1981	Shoreline Study	Mapped shorelines vs Climate	Eastern United States
Dodge et al., 1983	Coral Studies	Coral Reef Shorelines	Haiti
Flint, 1940	Shoreline Study	Stratigraphic Compilation	Eastern United States
Healy, 1975	Shoreline Study	Stratigraphic Mapping	Florida, United States
Imbrie et al., 1984	Sea-level Proxy Study	Oxygen Isotopes	Deep-ocean samples
Linsley, 1996	Sea-level Proxy Study	Oxygen Isotopes	Sulu Sea
Lisiecki and Raymo, 2005	Sea-level Proxy Study	Oxygen Isotopes	Deep-ocean samples
Ota et al., 1996	Shoreline Study	Mapped Shorelines	New Zealand
Shackleton, 1987	Sea-level Proxy Study	Carbon Isotopes	Deep-ocean samples
Skene et al., 1998	Sea-level Proxy	Oxygen Isotopes	Deep-ocean samples
Sterns, 1974	Shoreline Study	Mapped Shorelines	Hawaii and Australia
Waelbroeck et al., 2002	Sea-level Proxy Study	Oxygen Isotopes	Deep-ocean samples

Finally, dynamic topography was examined. Rowley et al. (2013) modeled elevation changes along the eastern United States since 3 Ma resulting from topographic changes created by flow within the mantle (Bertelloni and Gurnis, 1997). Calculations for each of these processes for each formation are reported in Table 3.7.

RESULTS

The Pleistocene marine section of the SC coastal plain is composed of 8-preserved sea-level highstand formations at the present-day surface separated by scarps (Figs. 1 and 3). Our mapped RSL elevations for each formation (from its associated scarp toe) relative to modern sea level (MSL) are: Marietta unit +42.6 m, Wicomico Formation +27.4-28.9 m, Penholoway Formation +21.3-22.8 m, Ladson Formation +17.4 m, Ten Mile Hill Formation (TMH) +10.7 m, Pamlico Formation +6.7 m, Princess Anne Formation +5.2 m, and Silver Bluff Formation +3 m. After reviewing work from Virginia (Johnson and Berquist, 1989) and North Carolina (Mallinson et al., 2008) to the north and Georgia (Hoyt and Hails, 1974), and Florida (Healy, 1975) to the south, a distance of more than 1000 km, we concluded that the scarp toe elevations do not vary more than the topographic map error, and are currently within 43 m of MSL (Figure 3.3; Table 3.2). Cooke (1936) also noted this regional “stability” of the scarp toe elevations. One interesting item from our mapping was that the Silver Bluff deposits were the smallest and least developed of the systems. We interpret that the Silver Bluff highstand was of a shorter duration than the older deposits. Our elevations and stratigraphy are supported by Figures 3.1, 3.3, and 3.5.

Table 3.7- Contributions of each Process Affecting Relative Sea-level Elevation. Observed and isotope proxy- estimated elevations in meters above present sea level. All other values in meters.

	Contributions of each Process Affecting Relative Sea-level Elevation- Values in meters								
Highstand deposits	**Observed Scarp Toe elevation**	**Predicted elevation**	**Topographic error**	**Tectonics possible**	**Sediment loading**	**GIA remaining**	**HIA rebound maximum**	**Dynamic Topography maximum**	**Net Correction**
Marietta unit	42.6	-10 ± 10	± 1	3.2 to 8.0	-21.0	20	Not calculated	16.8	-23.7 to -28
Wicomico Fm	27.4 – 28.9	-25 ± 10	± 1	2.4 to 6.0	-13.4	20	Not calculated	10.0	-22.6 to -29
Penholoway Fm	21.3 – 22.8	-15 to -5 ±10	± 1	1.6 to 4.0	-8.7	20	Not calculated	7.4	-29 to -31
Ladson Fm	17.4	7 ± 10	± 1	0.8 to 2.0	-6.3	20	Not calculated	3.8	-19.3
Ten Mile Hill Fm	10.7	-5 ± 10	± 1	0.4 to 1.0	-2.0	20	Not calculated	2.1	-21
Pamlico Fm	6.7	5 to 7 ±1	± 1	0.24 to 0.6	-1.1	20	10.5	1.0	-8
Princess Anne Fm	5.2	-20 ± 10	± 1	0.16 to 0.4	-0.69	20	8.8 or 5.3	0.8	-15.2 to-18.5
Silver Bluff	3.0	-80 to -40	± 1	< 0.16	-0.31	10	6.5 or 1.3	<0.8	-17 to -22

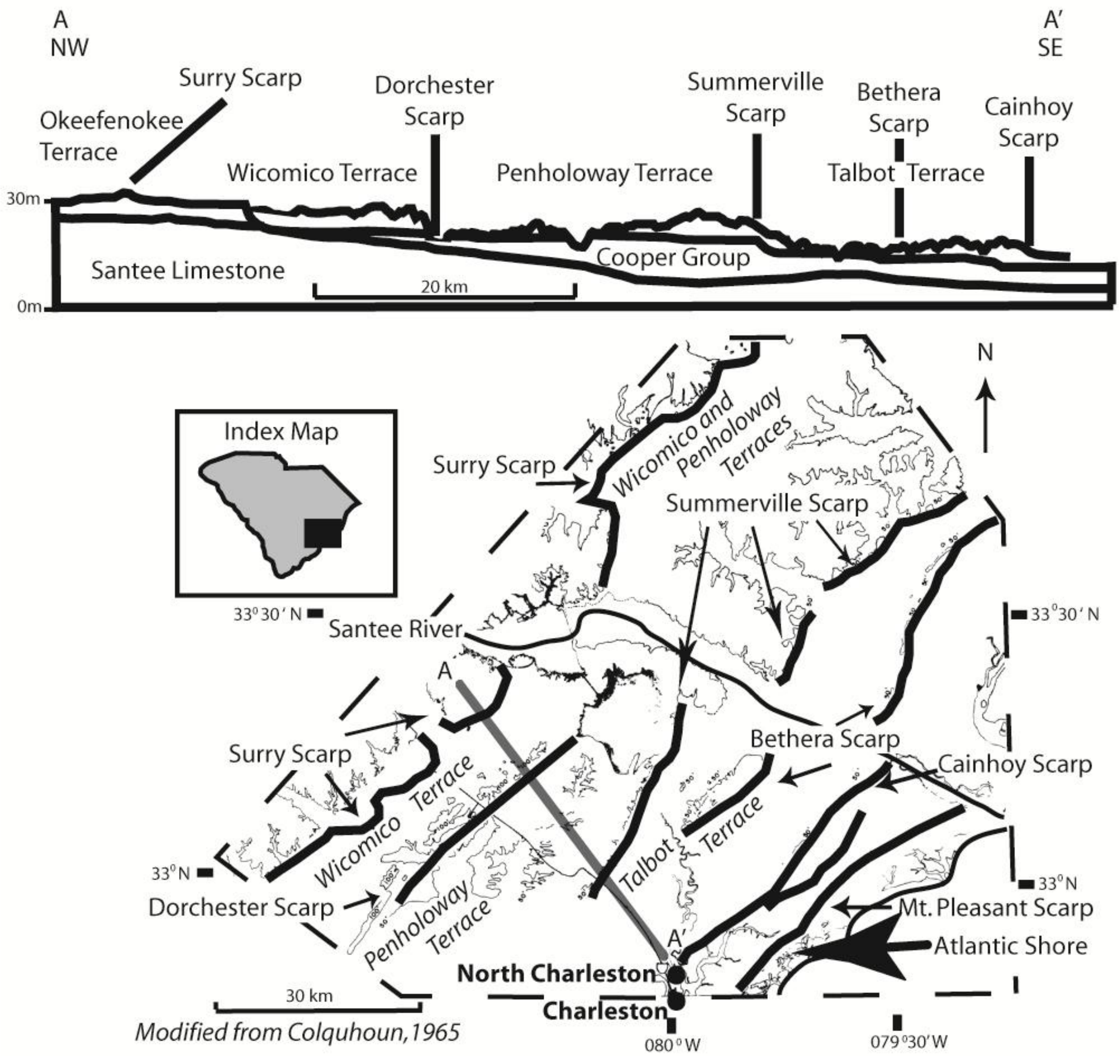


Figure 3.5- Colquhoun (1965) map of the Charleston, South Carolina area. The map and cross-section illustrate one set of stratigraphic concepts in the 1960's. Colquhoun continued to develop this concept and stratigraphy into the 1990's. This stratigraphy is adjacent to a conflicting stratigraphy to the north proposed by DuBar et al. (1974).

Note that generally each younger preserved highstand is seaward, and lower, in elevation of the next older formation resulting in offlap of the formations (Figure 3.3). This spatial arraignment is supported by the existing geochronology (Table 3.5). The general offlap geometry is not present in the estuarine areas, since later transgressive deposits often overlap older estuarine deposits. Weems and Lewis (2002) indicated a similar pattern in their maps of the Charleston, SC area. Note that neither regressive system deposits, lowstand materials, or formations without surficial exposure nor evidence of preexisting highstand deposits entirely removed by erosion were identified.

The mapped results do not agree with various global sea-level reconstructions (Imbrie et al., 1984; Linsley, 1996; Shackleton, 2000; Waelbroeck et al., 2002), except for the Pamlico Formation (Figure 3.4) To understand these offsets, we considered possible regional factors that might change the their elevation since their formation. These are: tectonics, erosional unloading/depositional loading, glacio-isostatic adjustment (GIA), hydro-isostatic adjustment (HIA), and dynamic topography. The results follow and a summary is presented in Table 3.7.

The tectonic uplift rate (Dowsett and Cronin, 1990), assuming the rate has been constant and the assigned ages for the shoreline are correct, has an effect scaled to the age. Thus the maximum tectonic uplift for our formations is: Marietta unit 3.2 m to 8.0 m; Wicomico Fm 2.4 m to 6.0 m; Penholoway Fm 1.6 m to 4.0 m; Ladson Fm 0.8 m to 2.0 m; Ten Mile Hill Fm 0.4 m to 1.0 m; Pamlico Fm 0.24 m to 0.6 m; Princess Ann Fm 0.16 m to 0.4 m. The conflicting age data for the Silver Bluff Fm makes a better estimate problematic but it is less than the maximum of 0.16 m of the Princess Anne. The age data

(Table 3.5) are presented in the Discussion section along with a more detailed treatment of the calculated tectonic uplift.

GIA has a maximum effect proximal to an ice-load that decreases distally. Proximally, there is downwarping and distally there is rebound upwarping (the forebulge). SC is on the distal part of the forebulge related to Pleistocene North American glaciation. Potter and Lambeck (2003) modeled a far-field 20 m gradient between the central east coast of North America and Barbados, with North America being up and Barbados down, and our study area is somewhere along that gradient. GIA is considered further in the Discussion section.

HIA has a maximum effect offshore and decreases shoreward (Figure 3.6). To illustrate this effect for multiple shorelines, several iterations of a 2D model (OSXFlex2D software; Cardozo, 2013) were run for just the three youngest Pleistocene shorelines to calculate the instantaneous highstand HIA. The detailed HIA data is presented in detail in Table 3.8.

The modeled HIA rebound for each formation after its transgression in meters above deposited elevation is: Pamlico - 10.5 m, Princess Anne - 8.8 m and the Silver Bluff - 6.5 m (Table 3.7). These are the maximum values for HIA during each transgression. HIA for subsequent highstands produces a reduced effect on the older, inland formations after their rebound.

Table 3.8- Results from OSX2D crustal flexure model to determine hydro-isostatic effects of sea-level highstands on the mapped late Pleistocene shoreline positions. The results provide isostatic adjustments of older shoreline elevations during later high stands. Geophysical parameters are detailed in the Supplementary Material section.

		A		
		Pamlico		
		Shoreline	at 6.7 m MSL	
	h	x	t	u
Geographic Location	Water depth (m)	Distance Offshore (km)	Resulting rebound after regression (m)	Depression (m)
	0.00	-30	8.56	-8.56
	0.00	-25	8.96	-8.96
	0.00	-20	9.36	-9.36
	0.00	-15	9.75	-9.75
	0.00	-10	10.15	-10.15
	0.00	-5.0	10.54	-10.54
Shoreline	**2.50**	**0.0**	**8.42**	**-10.92**
	5.00	5.0	6.3	-11.3
	7.50	10	4.16	-11.66
	10.00	15	2.01	-12.01
	15.00	20	-2.66	-12.34
	17.50	25	-4.84	-12.66
	20.00	30	-7.05	-12.95
	22.50	35	-9.28	-13.22
	25.00	40	-11.54	-13.46
	27.50	45	-13.82	-13.68
	30.00	50	-16.14	-13.86
	32.50	55	-18.49	-14.01
	35.00	60	-20.87	-14.13
	37.50	65	-23.29	-14.21
	40.00	70	-25.75	-14.25
	42.50	75	-28.24	-14.26
	45.00	80	-30.78	-14.22
	47.50	85	-33.35	-14.15
	50.00	90	-35.96	-14.04
	52.50	95	-38.6	-13.9
	55.00	100	-41.29	-13.71
Shelf edge	57.00	105	-43.5	-13.5

		B		
		Princess Anne		
		Shoreline	at 5.18 m MSL	
	h	x	t	u
Geographic Location	Water depth (m)	Distance Offshore (km)	Resulting rebound after regression (m)	Depression (m)
Pamlico shoreline	0.00	-30	7.23	-7.23
	0.00	-25	7.55	-7.55
	0.00	-20	7.86	-7.86
	0.00	-15	8.17	-8.17
	0.00	-10	8.48	-8.48
	0.00	-5.0	8.78	-8.78
Shoreline	**4.00**	**0.0**	**5.08**	**-9.08**
	5.00	5.0	4.36	-9.36
	7.00	10	2.64	-9.64
	9.16	15	0.73	-9.89
	12.22	20	-2.08	-10.14
	15.27	25	-4.91	-10.36
	18.33	30	-7.76	-10.57
	21.38	35	-10.63	-10.75
	24.44	40	-13.53	-10.91
	27.50	45	-16.46	-11.04
	30.55	50	-19.41	-11.14
	33.61	55	-22.39	-11.22
	36.66	60	-25.40	-11.26
	39.72	65	-28.44	-11.28
	42.77	70	-31.51	-11.26
	45.83	75	-34.63	-11.20
	48.88	80	-37.76	-11.12
	51.94	85	-40.94	-11.00
Shelf edge	55.00	90	-44.14	-10.86

		C		
		Princess Anne		
		Shoreline	at -20 m MSL	
	h	x	t	u
Geographic Location	Water depth (m)	Distance Offshore (km)	Resulting rebound after regression (m)	Depression (m)
Pamlico shoreline	0.00	-30	4.34	-4.34
	0.00	-25	4.53	-4.53
	0.00	-20	4.72	-4.72
	0.00	-15	4.90	-4.90
	0.00	-10	5.09	-5.09
	0.00	-5.0	5.26	-5.26
Shoreline	**1.66**	**0.0**	**3.78**	**-5.44**
	3.33	5.0	2.28	-5.61
	5.00	10	0.77	-5.77
	6.66	15	-0.74	-5.92
	8.33	20	-2.27	-6.06
	10.00	25	-3.81	-6.19
	11.66	30	-5.35	-6.31
	13.33	35	-6.91	-6.42
	15.00	40	-8.49	-6.51
	16.66	45	-10.08	-6.58
	18.33	50	-11.69	-6.64
	20.00	55	-13.32	-6.68
	21.33	60	-14.96	-6.70
	23.33	65	-16.63	-6.70
	25.00	70	-18.31	-6.69
	26.66	75	-20.01	-6.65
	28.33	80	-21.73	-6.60
	30.00	85	-23.47	-6.53
Shelf edge	30.00	90	-23.56	-6.44

		D		
		Silver Bluff		
		Shoreline	at 3.0 m MSL	
	h	x	t	u
Geographic Location	Water depth (m)	Distance Offshore (km)	Resulting rebound after regression (m)	Depression (m)
Pamlico shoreline	0.00	-30	5.38	-5.38
	0.00	-25	5.61	-5.61
	0.00	-20	5.83	-5.83
PA shoreline	0.00	-15	6.05	-6.05
	0.00	-10	6.26	-6.26
	0.00	-5.0	6.47	-6.47
Shoreline	**4.00**	**0.0**	**2.67**	**-6.67**
	5.00	5.0	1.86	-6.86
	5.37	10	1.67	-7.04
	8.06	15	-0.85	-7.21
	10.75	20	-3.38	-7.37
	13.43	25	-5.92	-7.51
	16.12	30	-8.49	-7.63
	18.81	35	-11.07	-7.74
	21.50	40	-13.67	-7.83
	24.18	45	-16.29	-7.89
	26.87	50	-18.93	-7.94
	29.56	55	-21.60	-7.96
	32.25	60	-24.29	-7.96
	35.93	65	-26.99	-7.94
	37.63	70	-29.74	-7.89
	40.31	75	-32.49	-7.82
Shelf edge	43.00	80	-35.27	-7.73

		E		
		Silver Bluff		
		Shoreline	at -40 m MSL	
	h	x	t	u
Geographic Location	Water depth (m)	Distance Offshore (km)	Resulting rebound after regression (m)	Depression (m)
Pamlico shoreline	0.00	-120	0.85	-0.85
	0.00	-115	0.91	-0.91
	0.00	-110	0.97	-0.97
PA shoreline	0.00	-105	1.03	-1.03
	0.00	-100	1.10	-1.10
	0.00	-95	1.16	-1.16
	0.00	-90	1.23	-1.23
	0.00	-85	1.30	-1.30
	0.00	-80	1.37	-1.37
	0.00	-75	1.44	-1.44
	0.00	-70	1.51	-1.51
	0.00	-65	1.58	-1.58
	0.00	-60	1.66	-1.66
	0.00	-55	1.73	-1.73
	0.00	-50	1.80	-1.80
	0.00	-45	1.87	-1.87
	0.00	-40	1.94	-1.94
	0.00	-35	2.01	-2.01
	0.00	-30	2.08	-2.08
	0.00	-25	2.14	-2.14
	0.00	-20	2.20	-2.20
	0.00	-15	2.26	-2.26
	0.00	-10	2.32	-2.32
	0.00	-5.0	2.37	-2.37
Shoreline	**5.0**	**0.0**	**-2.59**	**-2.41**
	10	2.0	-7.55	-2.45
	10	5.0	-7.52	-2.48
	10	10	-7.49	-2.51
Shelf edge	10	20	-7.47	-2.53

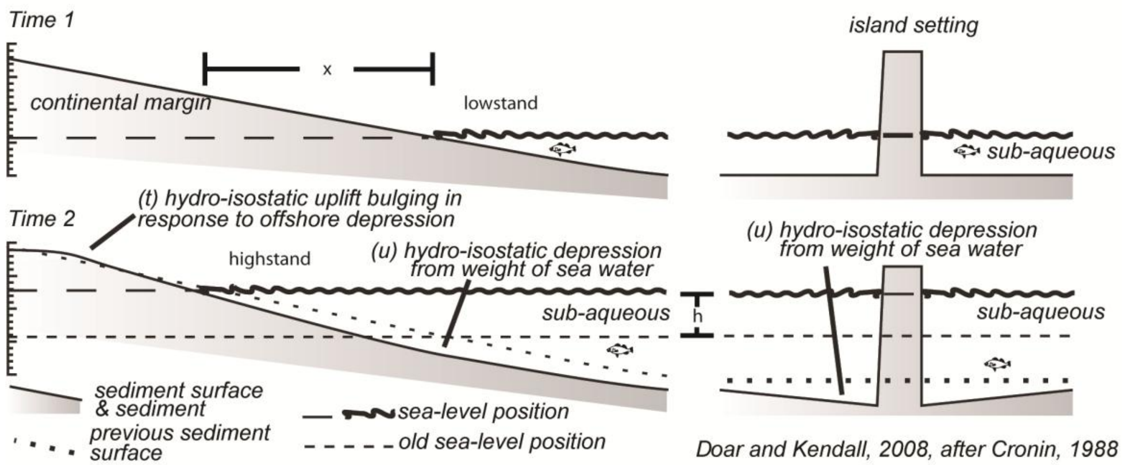


Figure 3.6- Examples of hydro-isostatic adjustment on an island setting and along a continental margin.

In Table 3.8 the calculated HIA rebound effect on the Pamlico from the Princess Anne highstand is 7.2 m and the calculated HIA rebound effect of the Silver Bluff on the Pamlico is 5.4 m and the Princess Anne is the 6 m. This rebound effect is the amount of HIA that later highstands impose on the earlier deposits and further complicating their adjustment history.

Dynamic topography calculated for the time of each formation was based on the modeling of Rowley et al. (2013) of positive vertical motion for eastern North America over the last 3 Ma. If this effect is linear, that extrapolates to a maximum of 16.8 m of uplift over the last 2 Ma. Table 3.7 contains the results of these calculations. In brief the maximum dynamic topographic uplift on the formations from oldest to youngest is; 16.8 m, 10.0 m, 7.4 m, 3.8 m, 2.1 m, 1.0 m, 0.8 m, and < 0.8 m.

DISCUSSION

Comparison of the Southeastern United States with other Sea-level Records

Our mapping has identified 8 Pleistocene highstand formations in SC. Review of sea-level curves from shoreline studies and isotope proxies elsewhere in the world (Table 3.6) show few interpret highstand elevations higher than modern sea level. For example, except for the Pamlico Formation, none of our highstand elevations fit with sea-level reconstruction predictions of Shackleton's (2000) (Figure 3.4). That all of our RSL elevations are currently higher than modern sea level is likewise almost unique. We now review each highstand in turn, oldest to youngest to assess any differences. Then we examine possible regional processes and their magnitudes which might have elevated the shorelines in SC. This exercise may offer insights on the cause of the apparent offset between our highstand data and sea-level reconstructions based on other proxy data (Figure 3.4, 3.7; Table 3.6). For this exercise we take Shackelton (2000) and Lisiecki and Raymo (2005) as a reference, but other reconstructions could be used.

The broad range of chronological ages for the oldest formations, the Marietta unit, Wicomico, and Penholoway, offer multiple possible MIS correlations for each (Figure 3.4; Table 3.5). Addressing the possible factors contributing to post-depositional elevation changes for each possible MIS correlation would take a considerable amount of space. However, as seen in Figure 4, it is safe to say that these oldest formations are higher than predicted by the sea-level reconstructions regardless of their exact ages.

The narrower estimated age ranges for the Ladson, Ten Mile Hill, Pamlico, Princess Anne, and Silver Bluff formations (Figure 3.4; Table 3.5) reduce the number of possible correlations with MIS stages. Based on our interpretations and using the existing geochronologies, our provisional correlations of our highstands to the predicted MIS sea-level highstands and relative offset are shown in Figure 3.4.

The Ladson Formation.

With an age of 450-400 ka (Table 3.5), the Ladson Fm is correlated with MIS 11. The Ladson’s shoreline is mapped at +17.4 m MSL (Malde, 1959; Weems and Lemon, 1984 a, 1989; Weems, Lemon, and Cron, 1985). The generally accepted sea-level reconstructions predicted the MIS 11 peak at

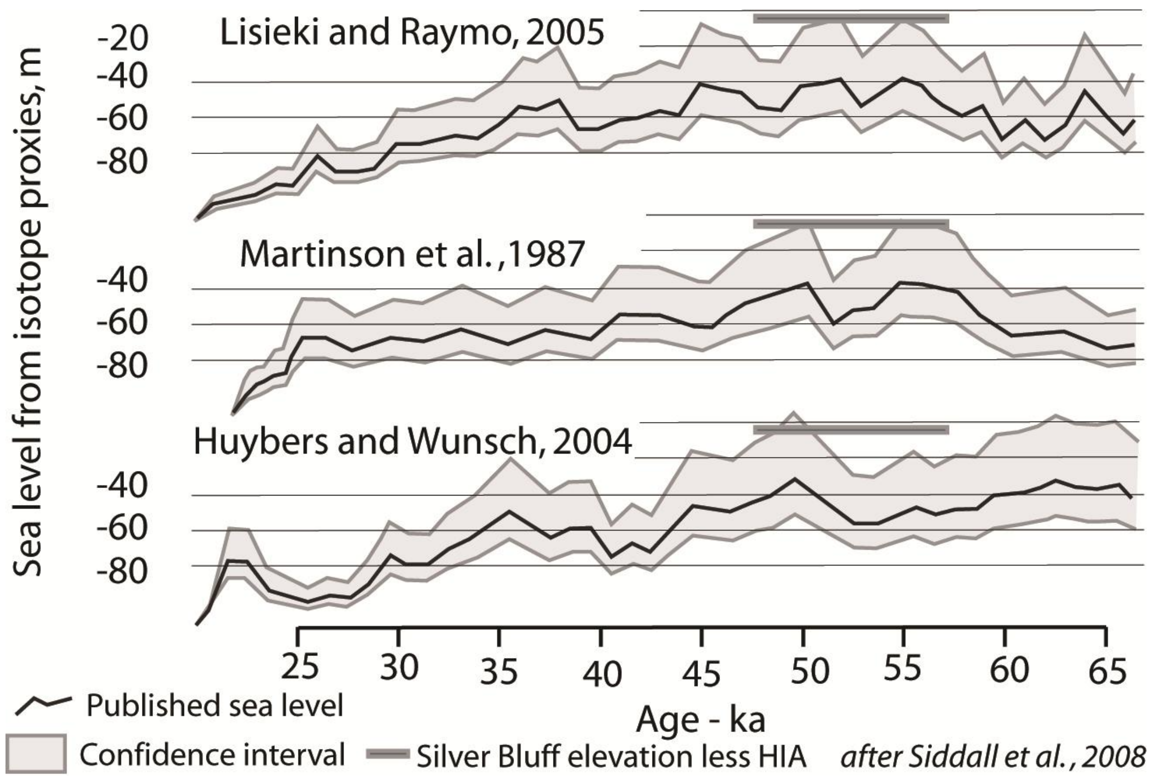


Figure 3.7- MIS 3 sea-level reconstruction curves with confidence intervals after Siddall et al. (2008). The shaded region represents the estimated range of elevations for any time. Note that the upper confidence interval limit of the curves may overlap the elevation of the Silver Bluff Formation after the removal of hydro-isostatic uplift as calculated in Table 3.8. The same may be true for the Princess Anne Formation (100-80 ka). If so this may explain part of the misfit with the reconstructions for these highstands.

+7 m MSL (±10 m) (Shackleton, 2000; Waelbroeck et al., 2002; Henderson et al., 2006). These uncertainties allow either a possible match of the two curves or an offset of 20 m. The elevation of the Ladson Formation is similar to other elevated shorelines. For example, in the Bahamas, Hearty and Kaufman (2000) reported a sea level of +18 to +20 m MSL for MIS 11. Hearty et al. (1999) reported a mapped MIS 11 sea level in Bermuda of +18 m MSL. Raymo et al. (2011) noted that Hearty et al.'s (1999) reported elevation may requires isostatic corrections but did not propose the amount of adjustment. Whether any such adjustment would apply to SC is unknown.

<u>The Ten Mile Hill Formation.</u>

With an age of 240-200 ka (Table 3.5), the Ten Mile Hill Fm (TMH) (Sanders et al., 2009) is correlated with MIS 7. The TMH shoreline was mapped at +10.7 m MSL and the sea-level curves predicted MIS 7 as -5 ±10 m (Thompson and Goldstein, 2006; Henderson et al., 2006). This confidence interval suggests sea level at least 5 to 25 m lower than our mapped elevations.

<u>The Pamlico Formation.</u>

With an age of 120 ka (Table 3.5), the Pamlico Fm is correlated with MIS 5e. The Pamlico's shoreline was mapped at +6.7 m MSL and the reconstructions predicted MIS 5e to be 5.7 to 7 m MSL with a range of ± 1 m. This elevation is supported by many onshore studies from different locations around the world (Table 3.9). For example, Hearty et al. (2007) reported a brief late 5e sea level of +6 to +9 m MSL and Kopp et al. (2009) reported a 95% probability that global sea level peaked at least 6.6 m higher than MSL.

Table 3.9- Publications list by author in agreement with our currently mapped elevation for the Pamlico Formation (+ 6.7 m) relative to modern sea level.

Publication	Location
Bard et al., 1990	Barbados
Bender et al., 1979	Barbados
Chappell, 1974	Huon Peninsula, New Guinea
Dodge et al., 1983	Haiti
Ludwig et al., 1996	Florida, USA, and Bermuda
Kopp et al., 2009	Worldwide
Kopp et al., 2013	Worldwide
Mallinson et al., 2008	North Carolina, USA
Parham et al., 2007	North Carolina, USA
Ota et al., 1996	New Zealand
Potter and Lambeck, 2003	East coast of USA
Skene et al., 1998	Deep-ocean samples
Stearns, 1974	Hawaii, USA, and Australia
Waelbroeck et al., 2002	Deep-ocean samples
Wehmiller et al., 2004	East coast of USA
Ward, 1975;	Huon Peninsula, New Guinea
Willis, 2006	South Carolina, USA

The general agreement of the Pamlico Formation with other areas indicates that no post-depositional regional adjustments, that might be required to bring younger formations into agreement, would put the Pamlico Formation into conflict.

The Princess Anne Formation.

With an age of 100-80 ka (Table 3.5), the Princess Anne Fm is correlated with MIS 5c and 5a. The Princess Anne was mapped at +5.2 m MSL and various reconstructions (Imbrie et al., 1984; Linsley, 1996: Shackleton, 2000) predicted MIS 5c and 5a as - 20 m MSL. The sea level suggested from the reconstruction estimates is 25 m lower than our mapped elevation (Figure 3.4).

The Silver Bluff Formation.

With published ages of ~100 and greater than 34 ka (Table 3.5), the Silver Bluff Fm is correlated with either MIS 5c or MIS 3. The Silver Bluff Formation was mapped inland of modern shoreline deposits and abutting and overlying the MIS 5c and 5a Princess Anne Fm (Figure 3.3 and 3.8; Table 3.2 and 3.4). Based on this stratigraphic context, we preferred an age less than that of the well dated Princess Anne Formation. However, that does not agree with studies citing ages of ~100 ka for the Silver Bluff (Zayac, 2003; Harris et al., 2005; Luciano and Harris, 2013). We are not able to resolve the age of the formation, but rather include the ages to allow comparisons for these two possibilities and the size of the offsets. Our mapped Silver Bluff shoreline elevation is currently +3 m MSL and reconstructions predicted MIS 5c elevations at -20 m MSL and MIS 3 highstands as -40 to -60 m (Linsley, 1996) or -60 to -80 m (Imbrie et al., 1984;

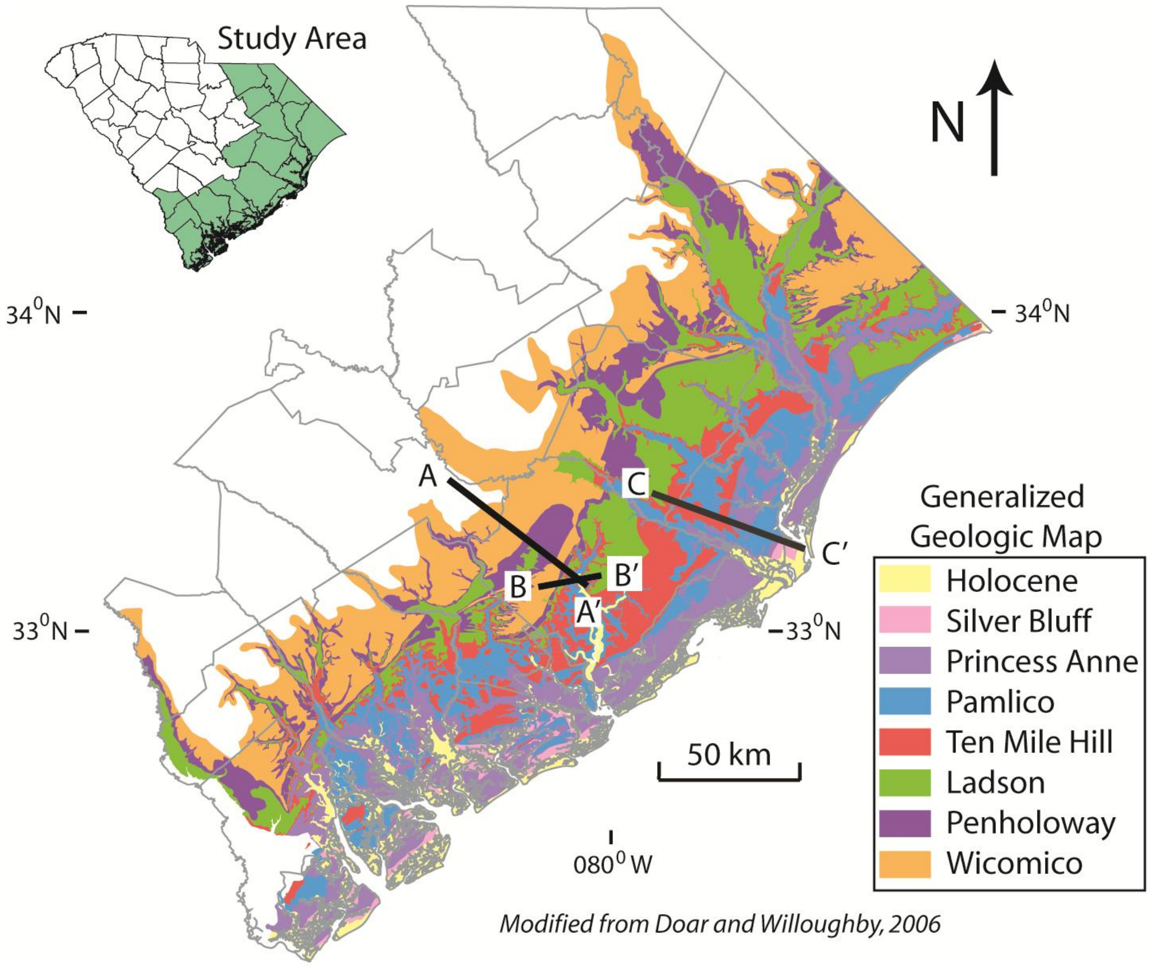


Figure 3.8a- Generalized surficial geology map of the delineated Pleistocene formations for South Carolina (Doar and Willoughby, 2006). This map results from the resolution of the conflicting stratigraphies proposed by Colquhoun (1974) and DuBar et al. (1974). Figure 3.2 in the paper is derived from this map. Cross-sections A, B, and C are presented in Figure 3.8b.

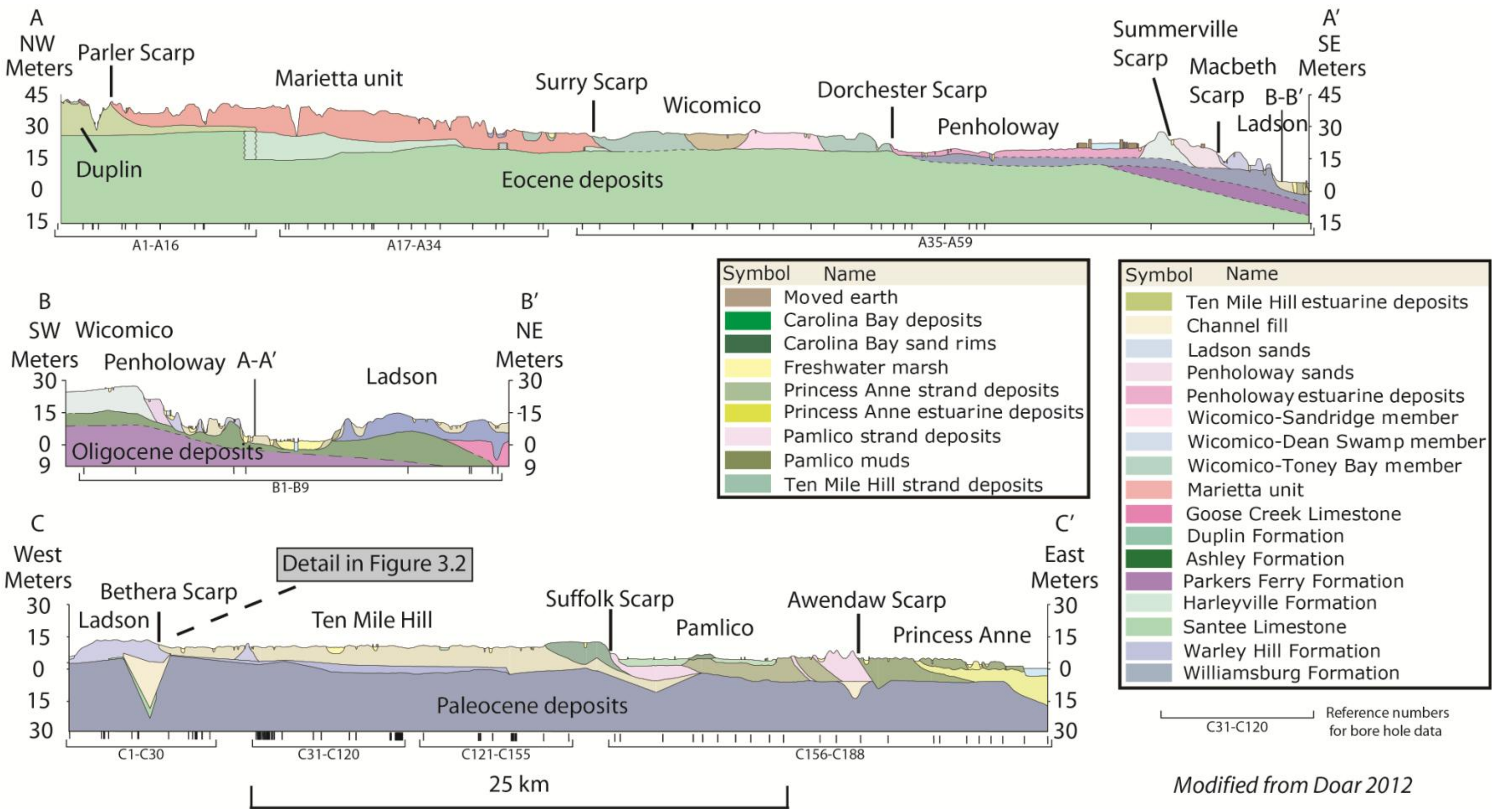


Figure 3.8b- Geological cross sections of the Pleistocene deposits along the Santee River, SC. The cross-sections are based on 1:24,000-scale geological mapping and borehole data. These sections include the Pleistocene marine stratigraphy and underlying pre-Pliocene deposits. Note the off-lap/ downstepping geometry of the Pleistocene deposits in each section. The black ticks below the cross sections are borehole locations within 2 km of the section line. The reference numbers provided below each cross section correspond to borehole identification numbers in Appendix A.

Henderson et al., 2006). Either case results in 23 to 83 m of difference between our observed elevations and the predicted elevations (Figure 3.4).

This is not the only study to observe possible MIS 3 elevations higher than reconstructions predicted. Wright et al. (2009) noted that the stratigraphic record for New Jersey's continental shelf MIS 3 deposits were noted as being currently 21 m below MSL. Mallinson et al. (2008) recorded MIS 3 deposits in the subsurface of the Pamlico-Albemarle sound estuary, North Carolina, 27 m below MSL. Scott et al. (2010) reported currently subaerial MIS 3 deposits from Virginia, similar to SC, but did not note their elevations. These examples support the interpretation that SC's stratigraphy is not an anomaly.

The Marietta, Wicomico, and Penholoway formations, even though they cannot be correlated exactly, are higher than sea levels reconstructed by the oxygen isotope stages. Of the Ladson, Ten Mile Hill, Pamlico, Princess Anne, and Silver Bluff formations, two do, or could, match the sea-level reconstructions with existing adjustment data (Ladson and Pamlico) and three do not (Ten Mile Hill, Princess Anne, and Silver Bluff).

The elevated shorelines on the Atlantic Coastal Plane are nearly unique in terms of their preset elevation above modern sea level. These high elevations are apparently at odds with sea levels reconstructed from isotope proxies, thus we examine the hypothesis that these high elevations are the result of some processes that operated over the region to explain these higher elevations. Specifically we consider: proxy conversion uncertainties, topographic error, tectonic uplift or subsidence, erosional unloading and sediment loading, glacio-isostatic changes, hydro-isostatic changes, and dynamic topography. We discuss these and their magnitude in turn next.

Possible Sources for the Lack of Fit between Observed Elevations and Predicted Elevations from other Sea-level Reconstructions

First, Siddall et al. (2008) pointed out that uncertainty of sea level derived from isotope curves can approach ± 30 m (Figure 3.7). Examples of the assigned confidence for MIS 3 are shown in Figure 3.7.

Second, since most mapped/observed elevations relied on the base map's accuracy, topographic error could have contributed to the lack of fit. The majority of maps used in SC have a 1.52 m (5 ft) contour interval. With each formation's scarp toe elevation consistently differing less than 2 m across the region, distances of several hundred km's north to south, we conclude that even though there is a 1 contour interval error possible, the map errors cancel out on the regional scale.

Third, regional tectonic uplift could uplift older shorelines and produce the down-stepping geometry (Table 3.6 and 3.9). Dowsett and Cronin (1990) reported an uplift rate for the Pliocene Orangeburg scarp of 0.02 to 0.05 x 10^{-1} mm/yr. The Orangeburg Scarp is as few as 7 km and as much as 50 km inland of all formations discussed herein. Thus, the calculated potential uplift of our formations, based on Dowsett and Cronin's (1990) rates, was no more than 8.0 m for the Marietta unit and less than 0.4 m for the Silver Bluff (Table 3.7). However, their data was sourced from Soller (1988). Soller's work assumed all uplift was tectonic and did not include any GIA or HIA in his calculations. Therefore, even if the use of these rates leads to errors, the magnitude of the possible adjustment is not enough to explain the mismatch noted above. In addition, there were no reports of tectonic motion within the area that could uplift the crust the maximum 83 m to fit the observed Silver Bluff elevations to the predicted elevations. Although tectonics may contribute, it alone could not explain the discrepancies in elevations, we consider other alternatives.

Fourth, erosional unloading of the crust inland of the shorelines and sediment transport offshore could tilt the entire region seaward to raise the landward shorelines. Over the past 15 Ma the Appalachian Mountains has eroded and uplifted while coastal plain downwarping occurred as shown by Pazzaglia and Gardner (1994, see their Fig 7). Their modeling, using Appalachian denudation and coastal plain deposition, produced a convex curve with a rate of 8.66×10^{-3} mm/yr at 100 km from the fall line. Their study focused on the central Atlantic margin but noted similar effects in the southern Atlantic margin. At this rate the maximum subsidence for the Marietta unit is ~21.0 m, the Penholoway is ~8.7 m, the Pamlico is ~1.1 m, and for the Princess Anne is 0.7 m, but this subsidence lowers, not increases, elevations.

Fifth, glacial isostatic adjustment (GIA) can alter the relative elevations of shorelines during and after deposition (Cronin et al., 1981; Davis and Mitrovica, 1996; Davis et al., 2008). The weight of glacial ice associated with North American ice sheet depressed the crust under and around the ice and created a distal fore-bulge. Peltier (2004) placed the center of the last glacial forebulge approximately beneath North Carolina with the flanks of the bulge in SC and Virginia. This bulge uplifted the Pleistocene elevations when the fore bulge was present. To the extent this operated during older glacial cycles, SC's coast underwent continuing crustal relaxation allowing relative sea level to transgress over it. For example, modeling of crustal flexure (Paulson et al., 2007) suggests a site in SC south of the maximum forebulge collapse of 0-1 mm/yr downward vertical motion consistent with an estimate of 1.5 to 1.9 mm/yr sea-level rise in the last 100 yr along the

SC coast (Davis and Mitrovica, 1996). The glacial cycles will introduce both downward and upward movements so the net effect should be close to zero for the shorelines that have experienced several glacial cycles although some difference may result as the volume of the North America ice sheet changes.

Estimating the effect of GIA within one glacial cycle, as is needed for the younger shorelines, is more complicated. During growth and decay of the ice sheet, we simply take the maximum of 2mm/yr rise here. This would introduce ~36 m of uplift during MIS 2. Supporting this, Potter and Lambeck (2003) modeled a gradient from Barbados up to the North American margin and conclude that the present-day crust is not in equilibrium due to ongoing subsidence of the glacial fore-bulge in the Virginia through North Carolina area with that 20 m of forebulge collapse remaining. They proposed that the North American MIS 5a shoreline and deposits formed when with GIA conditions were as today and 10 additional meters of current crustal relaxation (subsidence) remains from the last glacial cycle. Raymo et al. (2011) supported this when they concluded the crust is currently out of equilibrium and should continue to lower in elevation. The Pamlico shoreline is currently 1 to 2 m higher than the Princess Anne shoreline. Assuming the crust has been out of equilibrium, and the reconstruction's predicted difference between the Pamlico and Princess Anne of 25 m is correct, then more than 17 m of crustal relaxation post-Pamlico and pre-Princess Anne is required for them to be less than 2 m apart today. Post MIS 5a, both formations would have continued to lower as the MIS 5b forebulge collapsed. This would reduce 10 additional meters from the lack of fit predicted between the Pamlico and Princess Anne elevations compared to MIS 3 elevations in Figure 3.4 (i.e. Shackleton's (2000) curve) and would allow the Pamlico to fit the reconstructions and its current elevation difference with the Princess Anne, but would not completely resolve the Pamlico and Princess Anne's offset with the Silver Bluff.

Revised GIA model parameters may partially resolve the lack of fit between many of the observed elevations and predicted elevations. Engelhart et al. (2011) compared observed Holocene RSL changes using sea-level indicators along the U.S. Atlantic coast (provided in GSA Data Repository item 2011226, Appendix DR1) to GIA models (Peltier and Drummond, 2008; Argus and Peltier, 2010) utilizing two global ice sheet reconstructions (ICE-5G, Peltier, 2007; ICE-6G, Peltier, 2010) and two mantle viscosity models (VM5a, Peltier and Drummond, 2008; VM5b. Engelhart et al., 2011). The results lead Engelhart et al. (2011) to suggest an upper mantle viscosity of 0.25 x 10^2 Pa s (VM5b) for the mid-Atlantic coast of the United States, as opposed to the previously used 0.5 x 10^2 Pa s for the northern Atlantic (VM5a). Engelhart et al. (2011) propose that a laterally heterogeneous viscosity in the upper mantle improves the fit for the SE US: however, it left some mismatch.

Sixth, hydro-isostatic adjustment (HIA) can alter shoreline elevations relative to older shorelines. For a simple cases, such as islands, water weight added by deepening the water-column depresses the crust the island overlies (Figure 3.6) (Cronin, 1999) adding 20% of additional HIA to ESL change. Along a continental margin the HIA is not uniform from the edge of the continental shelf to inland areas. The added weight of water as it transgresses during interglacials depresses the crust beneath the continental shelf. This creates a forebulge some distance shoreward of the continental shelf edge with the fulcrum of this "levering action" seaward of the shoreline, thus uplifting distal formations and depressing proximal formations (Figure 3.6) and the converse during water removal.

This HIA could add a maximum of 20% to the change in RSL compared to the actual (ESL) in the offshore locations but would decrease inland of the shelf edge. Our estimates for the HIA for the Pamlico, Princess Anne, and Silver Bluff formations are 10.5 m; 5.3 to 8.8 m; and +1.3 to +6.5 m. These relative vertical movements make fitting our RSL elevations to the reconstructions more difficult.

For example, using the values in Table 3.7, when 10.5 m of HIA is added to the Pamlico Formation's present elevation of 6.7 m (ignoring GIA), it results in +17.2 m elevation. The maximum HIA from the Princess Anne is 8.8 m. Subtract that from the 17.2 m and the Pamlico's elevation relative to the Princess Anne should have been +8.4 m. The currently observed elevation difference between the Pamlico and Princess Anne is 1.5 m. Subtract that from the 8.4 m and 6.9 m as the remaining elevation to reconcile between these two highstands. If the sea-level reconstructions predictions of - 20 m MSL for the Princess Anne highstand are correct, then an additional 25 m of elevation has to be reconciled. HIA alone cannot account for this and creates more difficulty matching the observed elevations to the reconstructions predicted elevations.

Seventh, dynamic topography is the uplift or subsidence of the continental crust resulting from density anomalies created by convection cells in the mantle (Bertelloni and Gurnis, 1997). During times of rapid subduction the mantle flow exerts a downward pull on the continent, creating subsidence. When the subduction rate slows, the downward pull lessens and the crust rebounds. Rowley et al. (2013) modeled the dynamic topography effect for the eastern United States since 3 Ma. Their results (Fig. 2 of Rowley et al., 2013) show a complex effect of with spatial variations of as little as 0 m to as much as 25 m of uplift in SC. If their calculated rate is linear, that extrapolates to a maximum of 16.8 m of uplift for the Marietta unit and an estimated maximum uplift of 0.8 m for the Silver Bluff Formation (Table 3.7). While this effect may explain some of the offset between the shorelines and isotope reconstructions, dynamic topography is presently too poorly quantified to determine if it can explain all the offset.

Individually none of these processes can account for the offset between the mapped elevations and isotope reconstructions. For some of the shorelines, the collective addition of all or some of these effects may bring the two records into agreement. However, applying the interaction of these processes for all shorelines will cause new conflicts. Additional investigations may hone the first-order estimates presented here, but the highstand shorelines preserved along the Atlantic Coastal Plain may depend on the nature of the record preserved on terrestrial settings.

Hypothesis for the Formation of Terrestrial Highstand Features not Recorded in the Isotopic Record

Marine Isotope-based sea-levels reconstructions likely record different information from onshore lithostratigraphic-based maps. The onshore stratigraphy is based on preserved highstand deposits that record the highstand maxima and could be the result of short, high sea-level events. When such highstands end, estuarine sediments are abandoned at or near the maximum elevation. It is possible that sea-level reconstructions based on deep-ocean samples may not record these short highstand maxima due processes such as a water-column mixing lag. Shackleton (2000) reports that water chemistry changes may take up to 4 ka for water volume changes to be integrated into the record. For example, Siddall et al. (2008; references therein) note sea-level fluctuations of several tens of meters during MIS 3 and report rates of ice sheet growth during MIS 3 equal to 1-2 cm of sea level equivalent per year. That would be 10-20 m of sea-level change per 1 ka. Changes of this magnitude would require very high resolution records to be recorded in the deep ocean

We propose that some of the preserved onshore highstand formations could be evidence of brief sea-level excursions not recorded in the deep-ocean record. The Silver Bluff Formation may illustrate this. The Silver Bluff formation is offset with reconstructions produced from isotopic data (Figure 3.4). On the time scale for the formation of the Silver Bluff formation, the impact of tectonics, sediment loading, or dynamic topography are all less than a meter (Table 3.7). When the faster acting crustal adjustments are taken into consideration, then at least 10 to 50 m of sea level offset remains (Table 3.7). It may be possible for an excursion in the sea level on the order of ~10 m to transgress and form the Silver Bluff shoreline in less time than the ocean mixing lag. The speed of such sea level changes must be compatible with how fast the volume of the ice sheet can change (Raymo and Mitrovica, 2012; Roberts et al., 2012). This hypothesis further implies that only the highest sea-level events are recorded. Over the long term the highest in any time may be preserved by crustal uplift. Lower shorelines would be more complex because, for some time intervals more details are recorded by the shoreline deposits.

When attempting seemingly simple sea-level reconstructions, complex processes affecting changes in shoreline elevations, such as those evaluated herein, and processes that produce proxy sea-level estimates have to be evaluated before the two types of information can be directly compared.

CONCLUSIONS

We conclude that each of our highstand deposits is in unconformable contact with older formations at landward topographic scarps, and that the scarp toes (our indicators for former sea-level elevations) have consistent elevations (within map error) along the contacts with no regional offset or tilt. Our lithostratigraphic mapping of the coastal plain of SC has resulted in the identification of 8 preserved shorelines (scarps) and their associated immediately seaward formations (Figure 3.3). These elevations and current age assignments are: Marietta unit- +42.6 m, older than MIS 77; Wicomico Fm- +27.4 -28.9 m, MIS 55-45; Penholoway Fm- +21.3 -22.8 m, MIS 19 or 17; Ladson Fm- +17.4 m, MIS 11; Ten Mile Hill Fm- +10.7 m, MIS 7; Pamlico Fm- +6.7 m, MIS 5e; Princess Anne Fm- +5.2 m, MIS 5c and a; and Silver Bluff Fm- +3 m, MIS 3.

When these current elevations are compared with former sea level estimated by isotopic sea-level reconstructions (Table 3.6) many of them are offset. Two factors bring the two data sets into closer agreement: local processes across the Atlantic Coastal Plain that move the shoreline features and uncertainties in the isotope reconstructions. The mismatch may be reduced further by more detailed investigations of the processes, over various timescales, which have an impact on the present elevations of the shorelines. Issues with the commonly cited mantle viscosity models may incorrectly estimate the GIA and HIA for the SE US. Sediment redistribution, known tectonics, and dynamic topography can explain part of higher elevations in the older deposits but not the younger ones

We suggest that these onshore features may be the result of short lived highstands of sea level. These may be of shorter duration than recorded in isotope records but nevertheless leave a record on land. Long-term uplift would remove the older records but younger records are more susceptible to being removed by subsequent sea level highs.

The Pleistocene highstands demonstrate that reconstructions of past sea-level require careful evaluation.

ACKNOWLEDGEMENTS

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SUPPLEMENTARY MATERIAL

Geological Setting

This study focused on the coastal plain of South Carolina Atlantic seaboard (Figure 3.9). The original source data used in the paper are all from marine Pleistocene deposits and their regional authors are listed in Figure 3.9. We now assign the Marietta unit (informal) to the Pleistocene and therefore it is the oldest Pleistocene unit identified at the surface (Figure 3.3). The Marietta unit of South Carolina (DuBar et al., 1974) was

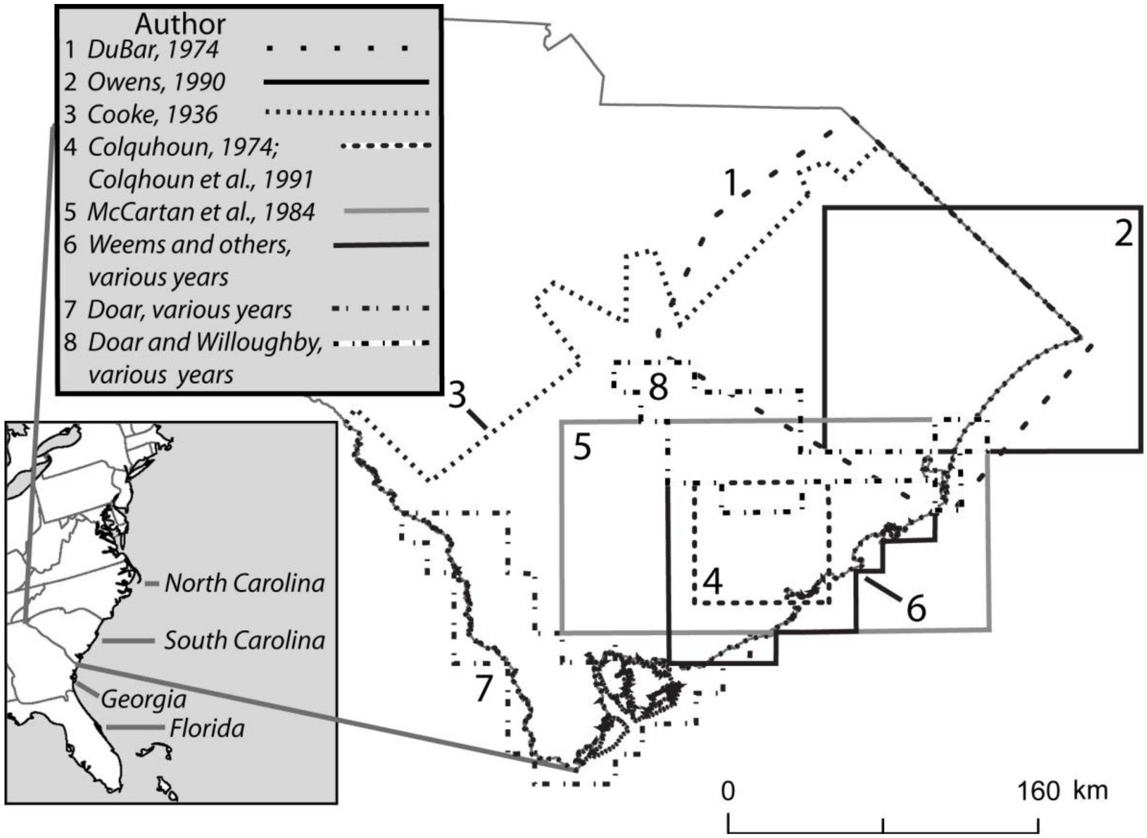

Figure 3.9- Reference map and workers index. The lithostratigraphy used in this paper is a synthesis of the maps produced in these publications. The geographic area covered by each author is noted by the number next to each different outline pattern. Some authors overlap the same areas.

formerly assigned to the Pliocene. The Pliocene age was based on the correlation with the Bear Bluff Formation age of 1.8-2.4 Ma (McCartan et al., 1982). The change of the Marietta unit's age assignment results from the proposed change in the base of the Pleistocene from 1.8 Ma to 2.558 Ma by the International Commission on Stratigraphy in 2009 (Gibbard and Head, 2009), and from age dates from Weems, Lewis, and Crider (2011) which revised the Marietta unit's age to 1.6 Ma.

Mapping Compilation

There is a well-established body of work related to these formations and features in South Carolina and their correlations to other states in the southeastern United States (Table 3.1 and 3.2).The geological formations established from mapping and their associated features, escarpments (scarp), terrace, unconformities, are used to establish that the toe elevation of the scarp is our indicator for former relative sea level elevation (terms defined in Table 3.4).

The sea-level indicators used in this paper are derived from geological mapping (Figure 3.1; Table 3.2 and 3.3). We assume elevation errors are small since many measurements were made across a substantially large area of study (~ 8000 km^2), as were measurements in comparable areas of map coverage in other studies while other studies have larger error ranges (confidence intervals) for possible elevations. For example, Waelbroeck et al. (2002) have estimated confidence intervals of ± 10 m. Our mapping, with elevations derived from USGS 7.5-minute 1:24,000 scale topographic maps, has a much smaller elevation error range.

Regional Stratigraphic Correlation

In southeastern North America the naming of many Pleistocene stratigraphic units are named after their associated geomorphic features (i.e. Shattuck 1901a; 1901b; 1906; Clark et al., 1912), and predate the now-standard North America Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005). For example, a terrace and its genetically related subsurface sedimentary deposits often share the same name, as in the Pamlico terrace and Pamlico Formation (Clark et al., 1912).

Correlatable formations, and geomorphic features, are critical to interpreting relative sea-level history. Locally there are difficulties correlating some of the stratigraphy and geochronology this has resulted in some inconsistent stratigraphic assignments. These differences in stratigraphy can confuse the correlation of formations with Marine Oxygen Isotope Stages and modeling isostatic corrections. We provide a summary of the evolution of the stratigraphy for reference.

During the 1960's and 1970's, Colquhoun (1974) and DuBar et al. (1974) both proposed stratigraphies for the Pleistocene of South Carolina. Colquhoun (1974) proposed a stratigraphy based on Cooke (1936) in the Charleston, SC area (Figure 3.5). DuBar et al. (1974) produced a generalized geological map of Neogene formations in NE South Carolina and SE North Carolina (Figure 3.10), creating a different stratigraphy from Cooke and Colquhoun. The resulting competing stratigraphies (Cooke vs. DuBar) for the same-aged sediments have produced complications for later workers. For example, based on remapping currently underway by the South Carolina Geological Survey (Doar, 2012), we feel that the samples attributed to the Canepatch (DuBar et al., 1974) were derived from three separate depositional episodes that may correlate to the

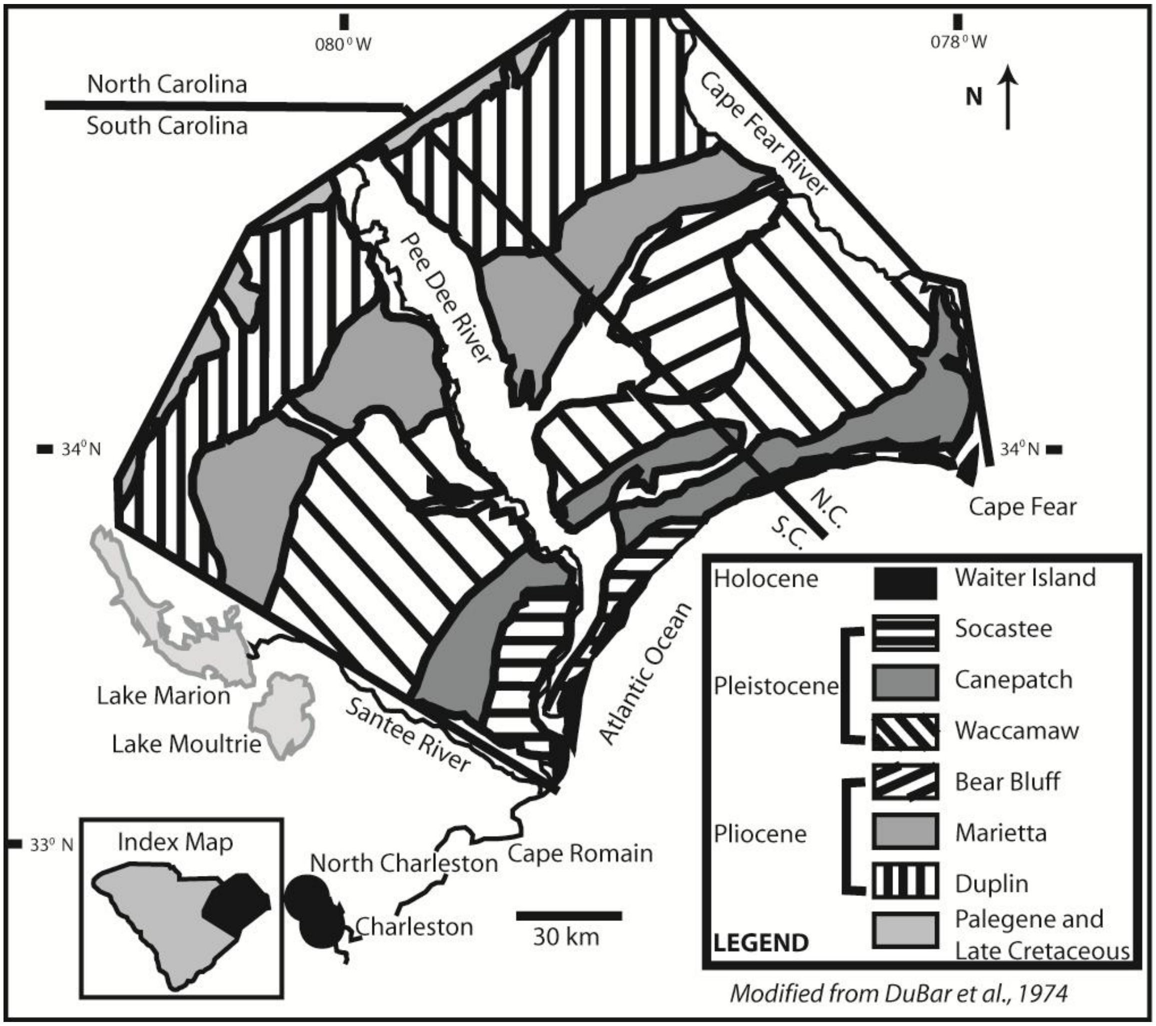

Figure 3.10- Generalized Neogene geology map from DuBar et al. (1974). The map illustrates one set of stratigraphic concepts in the 1960's. This stratigraphy is adjacent to a conflicting stratigraphy to the south proposed by Colquhoun (1965) and Colquhoun et al. (1991).

Ten Mile Hill, Pamlico, and Princess Anne Formations (Figure 3.4) just as the Talbot terrace of Colquhoun (1974) is divided by the Bethera scarp and composed of two depositional episodes- the Ladson and Mile Hill formations.

Quaternary geochronologic data for the area are available from numerous studies (e.g., Colquhoun, 1962; Wehmiller and Belknap, 1982; McCartan et al., 1984; Szabo, 1985; Wehmiller et al., 2004; Mallinson et al., 2008; Wehmiller et al., 2010) and all of the geochronological data used herein, except for our ^{14}C data (on file at the South Carolina Geological Survey), is sourced from existing publications.

Our mapping (Table 3.3), and the mapping noted in Table 3.1 and 3.2 (e.g. Hoyt and Hails, Colquhoun, Healy, Weems and multiple workers, Berquist and multiple workers), all use a directly correlatable stratigraphy (Table 2 SM). Doar (2012) mapped three highstands adjacent to the Santee River near Georgetown, S.C. as Ten Mile Hill, Pamlico, and Princess Anne Formations yet DuBar et al. (1974) mapped the same area as the Canepatch or Socastee Formations (Figure 3.3). Wehmiller and Belknap's (1982) explanations were complicated by this same stratigraphic confusion, particularly when attempting to date the Pamlico deposits correlated to samples from the Canepatch of DuBar et al. (1974) and the Wando of McCartan et al. (1980). The dates range from 74 ka to 180 ka. In the Charleston, S.C. area, Wehmiller and Belknap (1982) mention that four coral Uranium-series dates were 90-120 ka. Cronin et al. (1981) report dates from the Wando Fm of 139-87 ka. We feel that these samples are from two separate depositional episodes; the ~ 139-120 ka dates are from the Pamlico Formation and the 90-87 ka dates are from the Princess Anne Formation. We support this interpretation with two additional data sets. Between Charleston and Georgetown, Willis (2006) reports Optically

Stimulated Luminescence (OSL) dates of ~100 ka (± 18.15 ka) (Table 1 of paper) for mapped Princess Anne deposits. Also, York et al. (2001) report a Uranium-series date of 80 ka from mapped Princess Anne deposits south of Charleston and Wehmiller et al. (2004) also report Uranium-series coral dates from Charleston-area Princess Anne deposits of 75.5+/- 9.8 ka and 85.5+/- 10.8 ka. Additionally, since it was established as a formation, the Canepatch Fm has been restricted by various workers (Cronin, 1980; Soller and Mills, 1991) and no longer encompasses the entire stratigraphic and chronological ranges. The restrictions to the Canepatch places the interpretations of the Socastee Formation into question. Any previous models based off of the Canepatch or Socastee Formation's data may have issues related to the lack of detail as to which Marine Isotope Stage the samples were collected from (5e, 5c, or 5a). The Wando Formation used by the USGS encompasses 2 sets of highstand deposits (MIS 5e and 5a). Any models based on data from this formation may not be as accurate as models based on the ages and elevations of the separately-mapped highstands.

The 100 ka age for the Silver Bluff reported by Zayac (2003) from the Beaufort, S.C. area is suspect since it has been related to the stratigraphic context of the Princess Anne Formation landward of the sample site (Doar, 2003 g). Possible explanations for this older than expected age are: the sample area may have been incorrectly identified during our mapping; or the cores used may have crossed an unconformity and sampled from the underlying unit. The work of Zayac (2003) was focused only on the restricted area of Hunting Island State Park in South Carolina, whereas the Silver Bluff Formation mapped as stratigraphically higher than the Princess Anne Formation in more than 12 quadrangles (Table 3.10).

Table 3.10- List of map products by author that identify the Silver Bluff Formation.

Publication	Map Scale
Colquhoun, 1974	Regional
Hoyt and Hails, 1974	Regional
Weems and Lemon; 1985; 1993	1:24,000
Weems and Lewis, 1997	1:24,000
Doar, 1999; 2000; 2001b; 2002b;	1:24,000
2002d; 2003e; 2003g; 2003h	1:24,000

Our samples for carbon dating have all given ages of >48,000 ^{14}C BP (GX-33442 and GX 33448). Based on these data, the possibility exists that samples, which yielded ^{14}C ages of ~ 34 ka (Weems and Lemon, 1993) could have been contaminated with modern materials and represent composite dates of older deposits. Conservatively, we interpret that the Silver Bluff deposits are older than Holocene and younger than 100 ka.

Glacio-isostatic Adjustment Data

Several sets of workers have produced models to calculate the glacio-isostatic effects along the Atlantic coast of North America resulting from the last glacial maximum (LGM). The interpreted glacio-isostatic adjustment (GIA) from those models provides insight into the post-depositional elevations changes to mapped shorelines along the coast (Peltier, 1994; Potter and Lambeck, 2003). A note of caution should be made here- if these GIA models use onshore observations as calibration points, then refinements in the stratigraphy and geochronology should be addressed. For example, the issues with age-dates in South Carolina for the MIS 5 deposits noted in the Stratigraphic Correlation section above can add significant errors to any calculations of elevation. The range of ages for the Canepatch Formation (DuBar et al., 1974), Wando Formation noted in Cronin et al. (1981), and the Charleston area samples from Wehmiller and Belknap (1982) encompass MIS 5 e through MIS 5a. MIS 5 e and MIS 5a were mapped as highstands in the area- the Pamlico Formation (+ 6.7 m MSL) and the Princess Anne Formation (+ 5.18 m MSL). Colquhoun (1974), Hoyt and Hails (1974), Healy (1975), and Doar (2012) all map those separate highstands. The age of the Pamlico deposits is ~ 120 ka and the age of the Princess Anne deposits is 100 to 78 ka.

Hydro-isostatic Adjustment Data

Hydro-isostatic down-warping and rebound can alter relative shoreline elevations during and after deposition independent of GIA. Along a continental margin where the water does not depress the entire crustal mass, the process is very similar to glacial isostasy. The added weight of water as it transgresses during interglacials can depress the crust beneath the continental shelf and coastal plains. This can lever the crust downward with the center of the continent acting as a fulcrum, or it can create a fore-bulge some distance shoreward of the continental shelf edge with the fulcrum seaward of the shoreline (Figure 3.7). When the water is removed from the shelf the crust reverses direction. The rate and magnitude of crustal deflection is determined by weight of the added water column, the crust thickness, and mantle density. Table 3.8 contains the results of a 2D model (OSXFlex2D software; Cardozo, 2012) for calculating the instantaneous hydro-isostatic effect of water depth change from off the shelf edge inland to the mapped shorelines. We based the differences in water depths for each formation for the modeling on our mapping. The Young Modulus used was 70 Gpa. The Poisson Ratio was 0.25. The elastic thickness of the crust is 60 km and is based on the elastic thickness of viscosity model VM5a in Peltier and Drummond (2008). The mantle density used was 3,300 kg/m^3 with the density contrast being 3,300-1.025 kg/m^3 (the average density of sea water) = 3,298.98 kg/m^3. The water depth changes used were the equivalent to modern bathymetric depths. The total distance onshore and offshore is noted in Table 5 with 0.00 as that highstand's shoreline position. In the table, the value of "x" is the distance in km from the shoreline (negative numbers are km inland from shoreline), while "t" is the new topographic elevation in meters at each distance, and "u" is the net elevations change in meters (negative values indicate uplift). The model iterations were run assuming the bathymetric depths at each distance offshore at the start. The water was removed and the rebound magnitude (u) and the new elevation of the profile compared to its starting RSL elevation (t) was calculated from 30 km inland of that shoreline to the modern continental shelf edge. The 30 km distance inland captures the isostatic rebound effects on the next one or two inland scarps except for the MIS 3 deposits reported on the shelf by Harris et al. (2013). The distance inland use for the MIS 3 shelf deposits is 120 km in order to calculate the effects on the Pamlico and Princess Anne deposits.

The post HIA rebound topographic deflection is no more than +10.5 m for the Pamlico deposits. If ESL was +5.5-7 m MSL as predicted by other studies (Kopp et al., 2009; Kopp et al., 2013), then the HIA adds that 10.5 m to its elevation during MIS 5d. That resulting elevation is +16-17.5 m MSL.

The +4.9 m calculated HIA rebound effect on the Pamlico deposits for the predicted MIS 5a ESL of -20 m of the Princess Anne highstand is the amount that highstand depressed the Pamlico deposits. Removing that 4.9 m from the calculated post-MIS 5e rebound elevation of the Pamlico deposits (+16-17.5 m) results in a HIA-corrected predicted MSL elevation for the Pamlico of +11.1-12.6 m MSL. Currently the difference in mapped elevations of the Pamlico and Princess Anne shorelines is 1.5 m. The ~ 10 m of remaining elevation may be resolved with GIA or other processes.

The + 5.4 m calculated HIA rebound effect on the Pamlico deposits and the +6 m calculated HIA rebound effect on the Princess Anne deposits, resulting from the +3 m MSL for the Silver Bluff highstand are the magnitude this highstand depressed those shorelines. If the predicted MIS 3 ESL of at least -40 m MSL (possibly -80 m) is correct, then the current difference in mapped elevations of 3.7 m and 2.2 m (respectively) versus the predicted MIS 3 elevation is not resolved by the 5-6 m HIA.

A final note to consider is that the 5e (Pamlico) and modern shorelines have experienced similar glacioisostatic conditions, and the elevations should remain consistent relative to each other, as they do. With Kopp et al. (2009) assigning a 95% probability to the MIS 5e sea level having an elevation of at least +6.6 m MSL, these consistent elevations being closer together than predicted by the generally accepted sea level curves offer the potential for further research into this problem.

CHAPTER 4

Conclusions

After reviewing the existing stratigraphic publications and adding data from recent geologic mapping, along with the consideration of current geological concepts, revisions to the geomorphology and geology of South Carolina's coastal plain are proposed. One named Pliocene and eight named Pleistocene erosional marine scarps are related to sea-level highstands that created South Carolina's surficial deposits. Pleistocene marine sediments first identified by their geomorphic properties as terraces, with additional geological data, can be identified and defined as separate alloformations. The internal sediments are genetically related transgression and highstand deposits, separated from other deposits by unconformities, with scarps and terraces as part of the diagnostic boundaries. Continuing to use the scarp and terrace nomenclature is an important part of the identification of the formations and their stratigraphic position but acknowledging the units as alloformations completes the conceptual picture.

The Transgressive Surface of Erosion is found to be the most useful surface for formation delineation. The Maximum Flooding Surface, where preserved, is the second-most useful surface. The identification of the transgressive lag or back barrier estuarine sediments related to the Transgressive Surface of Erosion is critical to understanding the stratigraphic relationships in the Middle and Lower Coastal Plains. Once this identification is completed, an easily recognizable map-scale record of Pleistocene transgressions exists.

One scarp is formally proposed, two are revised, and four are abandoned.

The *Bear Bluff Formation* is abandoned; its lower part is referred to the Goose Creek Limestone and its unconformably overlying upper part is referred to the Marietta alloformation. The *Talbot* is abandoned as it has been shown to be composed of separate alloformations with separate overlying terraces. The *Canepatch* and *Socastee* formations are abandoned: they cross established transgressive time-lines and are in conflict with the published ages of the alloformations.

The conclusion is that each of our highstand deposits is in unconformable contact with older formations at landward topographic scarps, and that the scarp toes (our indicators for former sea-level elevations) have consistent elevations (within map error) along the contacts with no regional along-strike offset or tilt. From oldest to youngest, the Pleistocene elevations and current age assignments are: Marietta unit- +42.6 m, older than MIS 77; Wicomico Fm- +27.4 -28.9 m, MIS 55-45; Penholoway Fm- +21.3 -22.8 m, MIS 19 or 17; Ladson Fm- +17.4 m, MIS 11; Ten Mile Hill Fm- +10.7 m, MIS 7; Pamlico Fm- +6.7 m, MIS 5e; Princess Anne Fm- +5.2 m, MIS 5c and a; and Silver Bluff Fm- +3 m, MIS 3.

When these observed elevations are compared with former sea levels estimated by isotopic sea-level reconstructions, many of them apparently are offset. Two factors bring these two data sets into closer agreement: local processes across the Atlantic Coastal Plain that move the shoreline features and uncertainties in the isotope reconstructions. The mismatch may be reduced further by more detailed investigations of the processes, over various timescales, which have an impact on the present elevations of the shorelines. Issues with the commonly cited mantle viscosity models may incorrectly estimate the Glacio-Isostatic Adjustment and Hydro-Isostatic Adjustment for the southeastern US. Sediment redistribution, known tectonics, and dynamic topography can explain part of higher elevations in the older deposits but not the younger ones

These onshore features may be the result of short-lived highstands of sea level. These may be of shorter duration than recorded in isotope records but nevertheless leave a record on land. Long-term uplift would remove the older records but younger records are more susceptible to being removed by subsequent sea level highs.

Refined isostatic models, tectonic models, dynamic topography models, age-dating, and sea-level reconstructions based on isotopic proxy data are required and must be considered before using paleo sea-level positions on continental margins.

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APPENDIX A: Borehole Identification and Location Information for Cross Sections

Identification of boreholes with location information from the cross sections in Figure 3.8. The Cross Section ID "A1" data corresponds to the location labels from each cross section. The Station ID "38-177" corresponds to the South Carolina Geological Survey boreholes logs on file at the survey. Easting and northing data are in NAD 1927.

Cross Section ID	Station ID	Easting	Northing
A1	38-177	546040	3707070
A2	38-164	547442	3706859
A3	38 - 329	547178	3705789
A4	38 - 333	546583	3704982
A5	38-167	548311	3706754
A6	38 - 98	547615	3704022
A7	38 - 328	549399	3706006
A8	38 - 94	549236	3704936
A9	38 - 184	549349	3703204
A10	38 - 338	549351	3703206
A11	38 - 337	550773	3702283
A12	38 - 325	551579	3702636
A13	38 - 324	552164	3703360
A14	38 - 95	551492	3702461
A15	38 - 96	552930	3701037
A16	38 - 321	552888	3700703
A17	38 - 322	554945	3700434
A18	38 - 326	555393	3700741
A19	38 - 97	555196	3698990
A20	38 - 305	555447	3697958
A21	38 - 304	555841	3697797
A22	38 - 102	557462	3698380
A23	38 - 298	556847	3696694
A24	38 - 227	558965	3698730
A25	38 - 303	557144	3696271
A26	38 - 225	559460	3697277
A27	38 - 103	560058	3696999
A28	38 - 224	560839	3696887
A29	38 - 218	560605	3695429

A30	38 - 71	561597	3694125
A31	38 - 216	563147	3694266
A32	38 - 219	563007	3693461
A33	38 - 47	564219	3692257
A34	38 - 228	564386	3692118
A35	38 - 229	565595	3690565
A36	38 - 48	566302	3690088
A37	38 - 230	567494	3688924
A38	38 - 231	569124	3688717
A39	8-310	571093	3688901
A40	38 - 49	569716	3687076
A41	8-257	571635	3687734
A42	8-314	572596	3688043
A43	8-261	573472	3686577
A44	8-259	572723	3684565
A45	8-258	575532	3685142
A46	8-330	574868	3682505
A47	8-306	577327	3682663
A48	8-332	576861	3681304
A49	8-333	577517	3681180
A50	8-313	579163	3682363
A51	8-334	578507	3680984
A52	8-335	580308	3680679
A53	8-323	579693	3679897
A54	8-324	581161	3679820
A55	8-325	581660	3679880
A56	8-317	582216	3679949
A57	8-396	588554.9	3674889.18
A58	8-391	592080.9	3669719.89
A59	8-390	593001.9	3667942.28

Cross Section ID	**Station ID**	**Easting**	**Northing**
B1	08-389	585056.7	3668990.94
B2	08-397	587596.1	3668640.72
B3	08-391	592080.9	3669719.89
B4	08-390	593001.9	3667942.28
B5	08-363	599657.5	3673601.13
B6	08-365	602684.1	3673170.52
B7	08-367	603415.9	3669842.59
B8	08-366	604111	3671466.99
B9	08-348	604164.3	3672542.49

Cross Section ID	Station ID	Easting	Northing
C1	45-230	619008	3693355
C2	45-265	619998	3691387
C3	45-238	620187	3691691
C4	45-232	620319	3692027
C5	45-233	620740	3692857
C6	45-246	621402	3691227
C7	45-257	621728	3691361
C8	45-247	621707	3691267
C9	45-258	621721	3691312
C10	45-256	621696	3691207
C11	45-248	621691	3691186
C12	45-253	621690	3691174
C13	45-250	621669	3691078
C14	45-249	621688	3691145
C15	45-254	621679	3691112
C16	45-255	621667	3691050
C17	45-259	621641	3690955
C18	45-252	621660	3691008
C19	45-251	621660	3690981
C20	45-231	623230	3691473
C21	45-237	624697	3693322
C22	45-266	624041	3690233
C23	45-271	624220	3690438
C24	45-270	624247	3690470
C25	45-269	624267	3690499
C26	45-267	624295	3690537
C27	45-268	624343	3690594
C28	22-0193	624692	3690993
C29	22-041	624692	3690933
C30	45-236	625416	3692226
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C33	22-065	627484	3691451
C34	22-0152	627484	3691451
C35	22-072	627378	3690993
C36	22-0153	627504	3691339
C37	22-064	627504	3691339
C38	22-063	627518	3691218
C39	22-0154	627518	3691218
C40	22-0155	627544	3691136

C41	22-062	627544	3691136
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C44	22-0185	627605	3690876
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